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1996 LAKE WINNIPEG PROJECT: CRUISE REPORT AND SCIENTIFIC RESULTS

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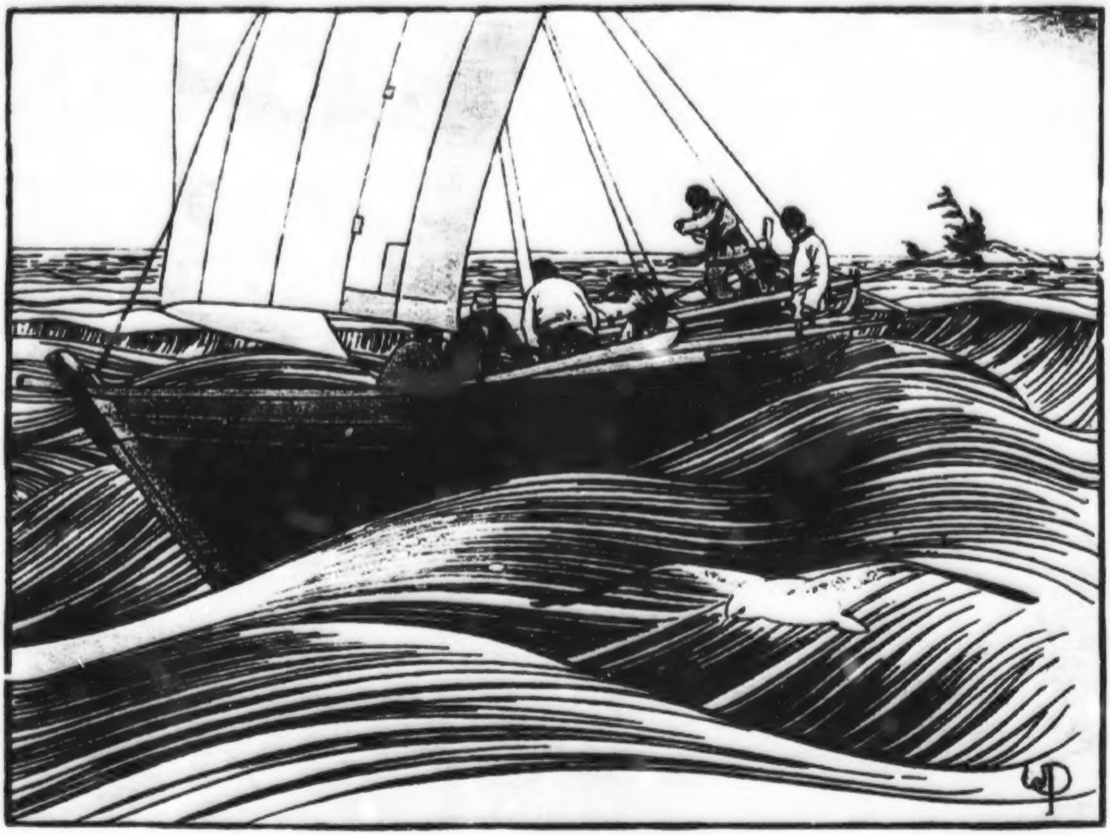

York Boat on Lake Winnipeg, 1930

Walter J. Phillips, R.C.A.
(1884-1963)

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1. Summaries

1.1 Executive Summary

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The Lake Winnipeg Project was launched by the Geological Survey of Canada (GSC) and Manitoba Geological Services Branch (MGSB) in 1994, with the support of Manitoba Hydro and the Manitoba Sustainable Development Innovations Fund, in order to support management of issues such as shoreline erosion and water quality. A four-week cruise of the Canadian Coast Guard Ship (CCGS) *Namao* in 1994 was followed by a similar effort in 1996. Low frequency air gun seismic, high frequency seismic, side-scan sonar, and coring operations, guided by real-time differential global positioning system (GPS) navigation, were supplemented by limnological and biological sampling carried out in cooperation with the Freshwater Institute. A five-year program of absolute gravity measurements and GPS data collection is monitoring uplift, a key factor in shoreline erosion, along a transect from Iowa to Churchill. Accompanying research on shoreline processes has included reconnaissance surveys in 1994, targeted investigations in 1996 and early spring 1997, and a month-long intensive effort in September 1997. Previously acquired wave data have been supplemented by data from three Waverider buoys deployed in 1996 and nearshore wave measurements in 1997. Although targeted follow-up research is anticipated, final outputs from the Lake Winnipeg Project are in preparation, for release in 2000-2001. Two major questions have been addressed by this work:

What is the structure of the Lake Winnipeg basin? Results have demonstrated that the structure of sediment and rock below Lake Winnipeg dramatically differs from expectations. Prior to the 1994 cruise, it was thought that sedimentary rocks extend close to the eastern shore, and that these rocks are buried by at most 15 m of sediment. In fact, sedimentary rocks extend only 10 km east from the end of Long Point, and terminate at a buried escarpment south of Hecla Island. Beyond these Paleozoic rocks, the acoustic basement beneath the lake consists of glacially scoured rocks of the Precambrian Shield. Sediments consisting almost entirely of proglacial Lake Agassiz silt and clay reach unanticipated thicknesses of over 50 m in the South Basin and over 100 m in the North Basin. Till and other gravel-bearing glacial and proglacial sediments are not extensive, but are present as formerly unrecognized major moraines at George Island and Pearson Reef. They also appear at several headlands projecting into the South Basin, where they serve to retard shoreline erosion. Sediments deposited in postglacial Lake Winnipeg rarely exceed 10 m in thickness. They rest on a regionally pervasive, low-relief, angular unconformity, and are cut by a complex array of furrows scoured by lake ice. Vigorous currents have stripped sediments from The Narrows and east of Black Island, producing the greatest water depths in the lake, over 60 m.

Are present-day environmental changes superimposed on long-term evolutionary trends? Without knowledge of the history of a lake, as recorded in its sediments, it is difficult to determine whether a basin was in a state of equilibrium prior to human intervention, or whether recent perturbation is only an addendum to more profound natural changes. The surveys have shown that Lake Winnipeg has, for centuries and millennia, been undergoing a progressive expansion. Sediment cores from the centre of the South Basin have revealed that Lake Winnipeg offshore sediments contain buried fossiliferous organic material that could only have been deposited at a pre-existing shoreline. Radiocarbon and paleomagnetic analyses of this material indicate that most of the South Basin was dry land at 4 ka BP (4000 radiocarbon years ago). The dominant control for southward lake expansion is crustal tilting, a result of the uplift of the Hudson Bay region following melting and breakup of the continental ice sheet around 10 ka BP. The rise of the lake has been punctuated by climate change, especially the shift from warm and dry to cooler and moist conditions around 4 ka BP, diversion of the Saskatchewan River into the North Basin at 4.7 ka BP, switching of the Assiniboine River from a path through Lake Manitoba to the North Basin over to the Red River and the South Basin around 4 ka BP, as well as progressive merging of several sub-basins from Playgreen Lake to the South Basin into one early lake about 2.9 ka, the present Lake Winnipeg.

1.2 Overview of the Lake Winnipeg Project

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INTRODUCTION

Lake Winnipeg is the eleventh largest lake in the world. With an area 25% larger than Lake Ontario, it stands as a major feature on the North American landscape. The lake is divided into two shallow basins (Figure 1). Depths do not exceed 19 m in the North Basin, or 13 m in the South Basin, although depths of as much as 60 m occur in the connecting narrow passages. Not only is the lake used for fisheries and recreation, it is vital to the Manitoba economy due to its role in hydroelectric generation. Despite its significance, however, Lake Winnipeg had until recently been the subject of little study. Aside from hydrographic charting (Canadian Hydrographic Service 1981; 1982; 1986) and surveys on surrounding land, the only previous comprehensive scientific effort was a 1969 limnological survey, led by the Freshwater Institute, that included sampling of bottom sediments at fifty sites and collection of several short sediment cores. Knowledge of the geology of Lake Winnipeg, and hence the structure and evolution of the basin, therefore had been limited to tenuous predictions based on studies on land. An offshore survey of Lake Winnipeg therefore was proposed by the staff of GSC and MGSB in 1993, on the basis of a need for an enhanced fundamental understanding of the lake.

PREVIOUS RESEARCH

Systematic GSC surveys of the shores of Lake Winnipeg were carried out in the 1890s by Dowling (1900) and by Tyrrell and Dowling (1900). Their reports include descriptions of the landscape and economy, to supplement description and classification of the Paleozoic sedimentary rocks along the western shore, the Precambrian rocks of the eastern shore, and the overlying Quaternary sequence. The Precambrian rocks were later analysed in more detail by Ermanovics (1970; 1973), Bell (1978), Brown (1981), and Weber (1990; 1996). The basal Paleozoic unit, the Winnipeg Formation sandstone, was examined by Macauley (1952), while the overlying carbonate rocks have been discussed by Baillie (1952), Stearn (1956), McCabe (1967; 1983), Bezys (1996a; 1996b), as well as by Bezys and Weber (1996). Additional work on the Quaternary geology of areas surrounding Lake Winnipeg has been reported by Antevs (1931), Klassen (1967; 1983), Tarnocai (1970), Grice (1970), Bannatyne and Jones (1979), Nielsen (1989), Henderson (1994), and McMartin (1996a; 1996b). Aggregate resources have been discussed by Groom (1985) as well as by Matile and Groom (1987), while groundwater resources around the South Basin have been addressed by Lebedin (1978) and by Betcher (1983; 1986a; 1986b). A postglacial pollen profile was obtained from a small lake on Long Point by Ritchie and Hadden (1975). These investigations of on-land Quaternary geology were summarized by Nielsen and Thorleifson (1996).

Scientific studies of the waters and biota of Lake Winnipeg were initiated in the 1920s and 1930s, including work on Red River waters by Ward (1926), on phytoplankton and other biological topics by Bajkov (1930; 1934), and on aquatic fauna by Neave (1932; 1933; 1934). Attention later shifted to engineering and development, as the prospects for lake level regulation and hydroelectric generation were defined (Lakes Winnipeg and Manitoba Board, 1958; Water Control and Conservation, Province of Manitoba, 1966; Kuiper, 1968). As decisions were made to proceed with this development, and as shoreline erosion received increasing attention, several University of Manitoba theses addressed shoreline processes and engineering (Buie, 1965; Veldman, 1969; Huggins and Edghill, 1969; Bray and Burgess, 1970; Cheng, 1972). Research also focussed on physical limnological topics such as wind setup and currents (Einarsson and Lowe, 1968; Hamblin, 1976; Lehn et al., 1976; Kenney, 1979). Preparation for lake level regulation included production of 1:2400 maps with a contour interval of 2 feet for areas within 3000 feet of the South Basin shore (Lockwood Survey Corporation Limited, 1972), a detailed investigation of South Basin shoreline erosion by Penner and Swedlo (1974), and publication of a shoreline erosion handbook (Manitoba Water Resources Division, 1977).

Ongoing limnological and fisheries research has been reported by Rybicki (1966), Evans and Stockner (1972), Crowe (1973), Davidoff et al. (1973), and Franzin et al.

(1996). A major advance in the breadth of knowledge regarding Lake Winnipeg resulted, however, from surveys conducted by the Freshwater Institute from the CCGS *Bradbury* in 1969, as well as later sampling that involved other agencies. Resulting work on nutrients was reported by Brunskill (1973) and by Brunskill et al. (1980b), on lake water composition by Brunskill et al. (1979a), on attenuation of light in Lake Winnipeg waters by Brunskill et al. (1979b), on morphometry and hydrology by Brunskill (1980a), and on the bottom sediments of Lake Winnipeg by Kushnir (1971), Allan and Brunskill (1977), as well as Brunskill and Graham (1979). Later work on nutrients was reported by McCullough (1996). Research on zoobenthos has been reported by Flannagan (1979), Flannagan and Cobb (1981; 1984; 1991; 1994), and by Flannagan et al. (1994), while work on zooplankton that pre-dated the Lake Winnipeg Project was reported by Salki and Patalas (1992) and by Patalas and Salki (1992). Research based at Grand Beach, on the eastern shore of the South Basin, directed at use of grain size analysis in the diagnosis of depositional environments, was conducted by Solohub (1967) and by Solohub and Klovan (1970).

Much uncertainty existed about fundamental aspects of Lake Winnipeg history until recent decades. Upham (1895, p. 217) thought that the latest and lowest Lake Agassiz shorelines are nearly horizontal over several hundred km, so uplift could not have had a significant impact on Lake Winnipeg. He also concluded that the original level of Lake Winnipeg was marked by a well-defined beach that had been reported between the mouths of the Winnipeg and Red Rivers, at 21 feet above present lake level. This was interpreted as the shoreline that had formed prior to downcutting of the outlet at Warren Landing, and he predicted with confidence that the shoreline would be found at nearly the same height around the whole lake (Upham, 1895, p. 221). Johnston (1946) later refuted this claim by showing that late Lake Agassiz shorelines along Lake Winnipeg in fact do rise significantly, although, through miscorrelation, he implied a complex pattern of uplift. The notion of little uplift in post-Lake Agassiz time was perpetuated by Elson (1967), who again suggested that the latest Lake Agassiz beaches were only slightly uplifted. A key factor in this uncertainty likely was the long-standing debate over whether Hudson Bay is still rising. This question was answered in the 1960s by data from the Churchill tide gauge (Tushingham, 1992). Gradual recognition that uplift has caused extensive expansion of Lake Winnipeg emerged in the writings of Penner and Swedlo (1974), Ringrose (1975), Pettipas (1976), and Thorleifson (1984). Field investigations meant to test this and other hypotheses subsequently were launched by Nielsen et al. (1987), Nielsen and Conley (1994) and by Nielsen (1996a; 1996b; 1998). Major contributions to the topic also have been made by geomorphic and lake-gauge analyses by Tackman and Currey (1996a; 1996b), Tackman (1997), and Tackman et al. (1998; 1999). This research allowed predictions of Lake Winnipeg expansion to be made, but confirmation would await comprehensive offshore surveys.

PROJECT COORDINATION

The Lake Winnipeg Project was enabled by endorsements and financial support provided in 1994 by Manitoba Hydro and the Manitoba Sustainable Development Innovations Fund, whose interest in the lake was bolstered by concerns regarding shoreline erosion. With confirmation of client endorsement in hand, major commitments of funding and equipment were received from three financial and logistical sources in the GSC. Links were established with ongoing research at the Freshwater Institute, as well as with several university-based research programs. Confirmation of the availability of the CCGS *Namao* allowed a go-ahead to be declared. An organizational meeting was held in Winnipeg in May 1994, and plans were made for a scientific cruise in August 1994 and a shoreline survey in September 1994.

The 1994 cruise began with a northbound geophysical survey, followed by a gear changeover at Grand Rapids, prior to a southbound coring phase. Limnological and environmental sampling were undertaken concurrently, and a grid of bottom sediment samples, coupled with biological and water sampling, was carried out from the ship's launch during the southbound coring phase. A two-week survey of the Lake Winnipeg shoreline followed, in September 1994.

Geophysical data were processed at GSC in Ottawa during the winter of 1994-1995. Sediment cores were thoroughly processed at GSC-Atlantic laboratories housed at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, in October 1994. Several thousand subsamples of the sediments were distributed for analysis at several laboratories across North America. Presentations summarizing the project were made at Geological Survey Open Houses in Winnipeg, in November 1994, and in Ottawa, in January 1995. A two-day scientific workshop, featuring 34 presentations, was hosted by Manitoba Energy and Mines in Winnipeg in March 1995. Support from Manitoba Hydro subsequently allowed a go-ahead for a five-year effort, co-ordinated by GSC-Pacific, to use twice-annual absolute gravity measurements and two new GPS receiving stations to measure uplift. A report summarizing progress to date was submitted to Manitoba Hydro in August 1995. GSC Open File 3113, summarizing scientific results of the Project in the form of 27 chapters, was prepared for release in March 1996 (Todd et al., 1996a). A full-day session consisting of 20 presentations on project and allied activity took place at the national conference of the Geological Association of Canada in Winnipeg in May 1996.

An additional phase of work was funded in 1996, including another offshore survey and the first year of a two-year shore processes study. These efforts were funded by GSC, Manitoba Hydro, and the Panel on Energy Research and Development. Three Waverider buoys were deployed to support wave research at the University of Manitoba. Shore process research intensified in 1996 and in March 1997, followed by a major effort in September 1997. Also in 1997, a display explaining the scientific results of the project was released as a poster on the World Wide Web (Todd et al., 1997; http://agcwww.bio.ns.ca/pubprod/of3434/index.html). A special issue of the Journal of Paleolimnology, including eleven papers on project work, was released in March 1998 (Todd et al. 1998a). Major scientific results were presented at the annual meetings of the Geological Society of America (Lewis et al., 1998b; Thorleifson et al., 1998) and the American Geophysical Union (Lewis et al., 1998a).

Although targeted follow-up research is anticipated, final outputs from the Lake Winnipeg Project are now in preparation. This Open File Report includes a report on the 1996 cruise, as well as data acquired since release of the earlier Open File Report. Separate Open File reports will assemble descriptive information and data from the 1997 shore processes field work. Additional scientific papers that may form the basis of another special edition of a journal will then be the priority activity.

NAMAO CRUISES

The central activity of the Lake Winnipeg Project has been offshore geophysical and coring operations conducted from the CCGS *Namao* in August 1994 (Todd, 1996a) and August 1996. The *Namao*, built in 1975 as a navigational aids tender by Riverton Boat Works, is 33.5 m long, 8.5 m wide, and has a draft of 2.1 m. Addition of sleeping accommodation for four in a trailer on the aft upper deck permitted eleven Coast Guard staff, a scientific crew of six, as well as day visitors, to participate in offshore operations.

The 1994 cruise was designated GSC cruise *Namao* 94-900. Equipment was transported from Dartmouth and Ottawa to the Coast Guard base in Selkirk by tractor-trailer. Construction of a temporary laboratory in the hold of the ship, equipment set-up, and modifications to the ship's electrical system were completed from July 30 to August 3. Surveying operations began mid-day on August 4, following a three hour passage from Selkirk to the lake. A series of geophysical survey lines, conducted as weather permitted, were completed on August 19. On August 20, the ship was changed over at Grand Rapids from geophysical surveying equipment to coring gear. The coring phase, from August 21 to 30, included a one-day visit to the ship by The Hon. Jon Gerrard, then Secretary of State (Science, Research and Development), as well as visits by several other guests. The vessel was tied up overnight in every case, at Gimli, Victoria Beach, Gull Harbour, Pine Dock, Matheson Island, Berens River, George Island, Warren Landing, or Grand Rapids. At the end of the cruise, two days were required to demobilise equipment.

For the geophysical survey, west-east transects, with south-north tie lines, were run in both the South and North Basins, as well as in the connecting narrows and islands area. No data were acquired in the southern part of the North Basin owing to high wind and wave conditions. Nonetheless, over 500 km of geophysical track lines were obtained. Lack of seismic penetration over broad areas, especially in the southern South Basin, was thought to be due to gas disseminated within the sediments. The low frequency seismic reflection system utilized a 24-channel seismograph, a 10 cubic inch sleeve gun operated at an air pressure of 1900 psi and fired at a 5-second interval, and an eel with 24 receivers spaced at a 5 metre interval. The Seistec high frequency (2-6 kHz) seismic system included a receiver towed from the upper deck crane to starboard from the stern. A surfboard-mounted boomer, firing at a 0.25-second interval, was towed from the starboard aft main deck. Under most weather conditions and a ship's speed of about 4 knots or 7.4 km/hr, the surfboard planed 1-2 m below the water surface. Every twentieth shot was suppressed to allow the sleeve gun system to fire. The sidescan sonar towfish was towed off the port bow by a block attached to the crane. An experimental deployment of a ground penetrating radar was housed in a twin-hulled craft. A marine magnetometer was operated as well.

Coring was conducted to sample the sediments and to verify stratigraphy and features identified in the geophysical records. Navigation was by GPS with real-time differential corrections obtained from a geosynchronous satellite relaying the Duluth, Minnesota reference signal. Coring sites were determined by first inspecting high-resolution seismic records, and by interrogating stored navigation files to obtain the location. A total of 60 m of core was obtained from thirteen sites in 1994, with length ranging from 2 m to 8 m. This included one deployment of the AGC wide diameter long gravity corer, six deployments of the AGC wide diameter piston corer, two deployments of the Murphy wide diameter gravity corer, seven deployments of the Benthos long gravity corer, and two deployments of the Benthos piston corer. Two sets of piston coring gear were lost during the 1994 cruise, due to unanticipated ease of penetration of the corer into the lakefloor sediments. Excess velocity of the core head weight when the piston encountered the stop resulted in breakage of the cable and fitting. The CCGS *Namao*, being designed as a navigational aids tender, is well suited for handling large equipment on the foredeck and for deployment over the side. The vessel is equipped with a 9-m cable boom having a 5-ton primary runner. The foredeck is approximately 8.5 m by 8.5 m with a raised hatch cover in the centre of the deck. The AGC wide-diameter and Benthos medium-diameter piston coring systems were the primary tools used on the cruise. The apparatus was rigged diagonally across the foredeck. A maximum barrel length of 9 m was rigged due to space and handling limitations and water depth. The core liner was extruded from the core barrels, cut into 5 foot-long (1.5 m) sections, sealed at the ends, labelled and stored upright in a core cooler on the foredeck. At the conclusion of the cruise, this core cooler was transported to the core storage facility at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia. Box cores were obtained at 10 sites in 1994, to obtain a high-resolution record of recent sedimentation. The apparatus recovered a 0.5-m square cubic sample from the lakefloor. Four 10-cm diameter tubes, aided by a vacuum pump, were used to core the sediments without disturbance.

In 1996, a second cruise was completed, *Namao* 96-900, in which emphasis was placed on confirmation and dating of the southward migration of the lake, and scouring of the lake bottom by ice. Outfitting of the CCGS *Namao* for the survey commenced at Selkirk on August 6, 1996. The initial portion of the cruise, from August 9 to 21, was devoted to geophysical surveys of ice scour features and lake bottom stratigraphy. In total, 238 km of survey lines were completed. A major innovation of the survey was the application of dual-frequency sidescan sonar, which distinguished recent from buried ice-scour features. Demobilization of the geophysical instruments and mobilization of coring gear was completed August 22 at Grand Rapids. A total of 134.8 m of core subsequently was obtained from 22 sites, including excellent intersections of sand bodies buried by fine-grained sediments in the South Basin. The cruise was less experimental and diverse than the 1994 effort. No further box coring, which had been very successful in 1994, was required, and geophysical surveys were limited to low frequency seismic, high frequency seismic, and sidescan sonar. Slightly different modes of core collection, variations in corer operation, and natural variations in sediment strength led to variations in the recovery of sediments, particularly the soft, low-strength Lake Winnipeg mud. In 1994, a long gravity corer was used after loss of two standard solid piston corers, but in 1996, a split piston corer was used.

GEOPHYSICAL SURVEYS

Seismic and sidescan sonar records obtained during the two *Namao* cruises have permitted an interpretation of the geometry of bedrock surface, of the distribution, thickness, and structure of sediments infilling the Lake Winnipeg basin, and of the nature of lake bottom morphological features (Todd and Lewis, 1996a; 1996b; Todd et al., 1998b). In most cases, a clear distinction between low-relief Paleozoic carbonate rock and high-relief Precambrian rocks can be made. In northern Lake Winnipeg, the eastern limit of Paleozoic rock is clearly demarcated 30 km west of the previous estimate of its position. In southern Lake Winnipeg, all or most of the Paleozoic sequence terminates at a prominent buried escarpment in the centre of the lake. This indicates that Paleozoic rock on the eastern shore, known from drilling and outcrops, is an outlier. Major moraines are apparent as abrupt, large ridges having a chaotic internal reflection pattern. These include the Pearson Reef Moraine, the George Island Moraine, and the offshore extension of The Pas Moraine. Little evidence for extensive or thick till was observed. Instead, fine-grained sediments deposited in glacial Lake Agassiz rest directly on bedrock over most of the lake basin. Hence an episode of erosion to bedrock was associated with the last glaciation and/or deglaciation. The Agassiz Sequence sediments are well stratified, drape underlying relief, and in some areas are over 100 m thick. In places, stratification in these sediments is disrupted, perhaps by dewatering. Southeast of The Pas Moraine (Long Point), disruption may be a result of a surge of thin ice and iceberg scour. Evidence of erosion of Agassiz Sequence sediments by recent currents was observed. The contact between the Agassiz sequence and the overlying Winnipeg Sequence sediments is a marked angular unconformity. The Agassiz Unconformity indicates up to 10 m of erosion in places. The low-relief character of this unconformity precludes subaerial erosion and the lack of till, moraines, or extensive deformation precludes glacial erosion. Waves appear to be the most likely erosional agent, either in waning Lake Agassiz or early Lake Winnipeg time. Winnipeg Sequence sediments, in places very thin, mantle most of the lakefloor. These sediments were deposited in Lake Winnipeg, are faintly stratified to massive, and reach about 10 m in thickness in deep water. The surface of the Winnipeg Sequence is ornamented by a complex array of furrows formed by the action of lake ice. Vigorous, episodic currents are thought to contribute to the construction of flow-transverse sand waves as much as 6 m high in a deep, narrow constriction in the lake.

OFFSHORE STRATIGRAPHY

Detailed interpretation of sediment seismostratigraphy and lithostratigraphy of sediments in Lake Winnipeg has been conducted by Lewis and Todd (1996a; 1996b) and by Lewis et al., this volume. This work is based on both low frequency and high frequency seismic records, and analysis of long cores obtained in 1994 and 1996. Above the Agassiz Unconformity, the Winnipeg Sequence appears as a transparent acoustic section grading downward to weak parallel reflections, and consists of soft dark olive grey clay-silt mud, faintly banded in its lower section. In the North Basin, the underlying Agassiz Sequence mainly appears as three intervals of parallel seismic reflections of variable amplitude, and the sediments consist of up to tens of metres of silty clay rhythmites, some up to 5 cm thick. At one site, a grey stony diamict likely deposited as till was cored under silty clay rhythmites. In the South Basin, the Agassiz Sequence is more complex, and consists of four seismic intervals. Where cored, the upper three intervals are stiff, banded silty clay and rhythmites, stiff silty clay rhythmites, and stiff faintly banded silty clay, respectively. This stratigraphic model, when combined with other observations, has permitted an interpretation of the evolution of Lake Winnipeg to be made, providing a basis for understanding trends in water level change and shore erosion, as well as providing a basis for assessment of former lake conditions, including the distribution and history of contaminant inputs.

The work is dependent on recovered sediments from 33 long core sites, many of which sample the two major seismic sequences. Core quality varied considerably. The quality of mud recovery was evaluated by comparing recovered sediment intervals with thicknesses determined by seismic reflection. Shortfalls in mud recovery by coring with 9-m long barrels range from zero to under 2 m most commonly, and to one extreme value of 3.4 m. Reference to seismic records, rather than measurements from cores, therefore is favoured for determining the depth below lake bottom or elevation of the Agassiz Unconformity, where seismic velocity has been measured in the sediment cores. Till is absent or so thin, i.e. <~1 m, beneath much of the lake that it cannot be resolved in the seismic reflection profiles. Distinctive packages of coherent, strong reflections in Seistec records give character to the Agassiz Sequence, allowing its subdivision into reflective facies intervals. Reflections show that the glaciolacustrine sediments conformably drape the underlying relief on bedrock or morainic surfaces. By comparison with core lithologies and physical properties, the coherent reflection facies are correlated to zones of silty clay rhythmites or laminated silty clay containing mm-scale silt laminae. Combined thicknesses of these sediments create layers >20 cm thick with differing acoustic impedances, the cross-product of sound velocity and bulk density. The boundaries between layers of differing impedance are the likely sources of the strong, coherent reflections. Within the Agassiz Sequence, these zones, with their visibly more numerous silt laminae, are thought to reflect glaciolacustrine deposition nearer an ice margin, the inferred sediment source, than sediments that produce a transparent seismic facies. Alternatively, the silt laminae might reflect periods of enhanced seasonal melting. The uppermost strong coherent reflection package in the North Basin correlates to interbedded sandy silt and clay and may originate by wave and current winnowing in an environment of declining lake depth.

A comprehensive program of analyses is supporting co-operative efforts to work out the stratigraphy of sediments in Lake Winnipeg. Use of macrofossils of terrestrial plants and insects to obtain radiocarbon ages for sedimentation and for the reconstruction of paleoenvironments, primarily with respect to shoreline proximity, has been co-ordinated by A. Telka (Vance, 1996; Vance and Telka, 1998). Paleomagnetic methods, in particular geomagnetic secular variation, were applied by King and Gibson (1996a; 1996b). Compositional analyses were carried out by Last (1996), Henderson (1996), and Henderson and Last (1996; 1998). Isotopic analysis of sediments and pore waters was directed by W. Buhay and R. Betcher (Betcher and Buhay, 1996; Buhay, 1996b; 1996a; Buhay and Betcher, 1996; 1998). Palynological investigations were conducted by T. Anderson (Anderson and Vance, this volume), while ostracode micropaleontology work was directed by Rodrigues (1996a; 1996b, this volume). Thecamoebians were investigated by Burbidge and Schröder-Adams (1996a; 1996b; 1998), and phytoplankton by Kling (1996a; 1996b; 1998), as well as work on diatoms by J. Risberg (this volume). This activity is permitting a thorough investigation of the history of sedimentation in Lake Winnipeg, and hence the history of the lake itself.

A reconstruction of Lake Winnipeg lake level history, taking into account northeastward regional uptilting due to glacioisostatic recovery and diversion of the Saskatchewan River to the lake, but without consideration of climate change effects, suggests that: 1) following recession of glacial Lake Agassiz after 8 ka, Lake Winnipeg began as a series of independent lakes in the North, South, and other local basins, each draining northward over a local sill; 2) local lakes transgressed southward and coalesced, with the North Basin finally controlling water level in the South Basin after about 2.9 ka; 3) since 4.7 ka, water levels throughout the basin have been augmented as a result of Saskatchewan River diversion and capture of lake-level control by the more rapidly rising Jenpeg sill 78 km north of Lake Winnipeg.

There is evidence, however, that climate played a major role in much of Lake Winnipeg history. Basal reflections within the Winnipeg Sequence provide abundant evidence of onlap. This, combined with observations of coarser basal sediments in cores and evidence of coastal onlap indicates that the Winnipeg Sequence sediments were deposited in a transgressive lake with increasing water level. Basal radiocarbon ages for the Winnipeg Sequence show that the onset of sedimentation in North Basin began with the predicted isolation from Lake Agassiz about 7.7 ka, but sedimentation was suppressed at southern sites in North Basin and in the South Basin until 5-4 ka. The delay in sediment accumulation is contrary to the predictions of lake evolution based on differential postglacial rebound which assume that lakes are always open and overflowing at their outlets. Water balance computations suggest that the early history of Lake Winnipeg was influenced by closed lake conditions induced by warmer and drier climates similar to modern climates in southeastern Alberta and southwestern Saskatchewan. Under such climates, the South Basin appears to have dried up in the mid-Holocene. A lake returned and switched to open conditions after 4.5-4 ka in response to the onset of a cooler and wetter climate. A shorter and milder episode of closed lake conditions is inferred for the North Basin. Diversions of the Saskatchewan River to North Basin at about 4.7 ka (McMartin, 1996; this volume), and the Assiniboine River to the Red River and the South Basin at about 4 ka (Rannie et al., 1989) or later (Last et al., 1994) are nearly coincident with the switch in lake status from closed to open.

PHYSICAL PROPERTIES OF THE SEDIMENTS

Sediment physical properties were measured on the gravity and piston cores collected in Lake Winnipeg (Moran and Jarrett 1996a; 1996b; 1998). The measurements of bulk density, acoustic velocity, magnetic susceptibility, and colour reflectance were made using non-destructive methods at a 1-cm spacing. These high-resolution data have been used to construct complete composite stratigraphic sections from a series of individual, discontinuous cores. These composite sections provide a baseline depth reference for interpretation of the stratigraphy. The density and shear strength data were also used to estimate sediment stress history for each of the major lithostratigraphic units and their variations across the basin. Rack et al. (1998) have conducted experiments on magnetic resonance imaging of selected cores. Whole core gamma-ray attenuation measurements were used to calculate the bulk porosity of the sediment at 1-cm intervals for comparison with the images. Image contrast and image intensities were found to relate to local porosity and magnetic susceptibility variations. In general, regions of the core with low signal intensity contain high porosity and low magnetic susceptibility. The best contrast between sediment layers was observed from regions of the core with high magnetic susceptibility. High signal intensity was observed from regions with low porosity and/or high magnetic susceptibility.

RADIOCARBON GEOCHRONOLOGY AND MACROFOSSIL ANALYSIS

Radiocarbon dating of bulk Lake Winnipeg sediments conducted by Lewis and Todd (1996a) yielded age estimates several thousand years older than a corresponding macrofossil age determination obtained by Vance and Telka (1998), indicating contamination likely derived from carbonaceous rocks in the drainage basin. Although no evidence of reworked coal or amber was observed in the sediments, Anderson and Vance (this volume) reports the existence of at least 10% pre-Quaternary palynomorphs within Lake Winnipeg South Basin sediments. Furthermore, calcareous fossils provided results that appear to be centuries to millennia in error presumably due to incorporation of old carbon. The project therefore shifted to exclusive reliance on dating of well-preserved macrofossils of taxa reliant on atmospheric carbon. Macrofossils of terrestrial plants and insects thus were used to obtain ages for sedimentation in Lake Winnipeg and for the reconstruction of paleoenvironments primarily with respect to shoreline proximity (Vance, 1996; Vance and Telka, 1998; Telka, this volume). Compared to conventional radiocarbon dating, the accelerator mass spectrometry (AMS) ^{14}C technique has the advantage of dating small samples (e.g. 0.5 mg) with high accuracy. This advantage, combined with the ability of a Quaternary macrofossil specialist to examine lacustrine sediments for identifiable macrofossils suitable for AMS dating, avoids problems such as hard-water effects and reworking of older sediments. Macrofossils not only provide a means of obtaining good chronological control but also provide paleoecological information on the depositional environment, which can be used effectively in reconstructions of paleoenvironments.

Useful age determinations were obtained from *in situ* carbonate fossils as well, ostracodes and molluscs. These were corrected for the hard-water effect, estimated from three samples of pre-bomb shells in southern Manitoba (Lewis et al., this volume). An ostracode sample provided the only AMS age determination for the Agassiz Sequence.

Reliable age determinations for the initiation and progress of Lake Winnipeg sedimentation were obtained from the majority of core intervals by screening several tens of ml of sediment at 0.25 mm, and by searching for and isolating well preserved fossils of taxa that derive their carbon from the atmosphere. Basal Lake Winnipeg sedimentation in the North Basin dates to the early Holocene, whereas corresponding age determinations for the South Basin cluster around 4.0 ka. Basal Lake Winnipeg sediments, especially in the South Basin, contain abundant shoreline taxa indicating proximity to shoreline. Fossils or lack thereof from overlying sediments suggest deepening water. Paleoenvironmental analysis and AMS dating of plant and insect macrofossils from Lake Winnipeg sediments have provided significant information on the sedimentological history and paleohydrology of the lake basin.

PALEOMAGNETIC STRATIGRAPHY

Paleomagnetic methods, in particular geomagnetic secular variation, have been applied to the Lake Winnipeg sediment cores by King and Gibson (1996a; 1996b) and King et al. (this volume). Geomagnetic secular variation (SV) is the temporal variation of the two components of the Earth's magnetic field (inclination and declination) and its intensity between polarity transitions. The peak-to-trough amplitudes of North American secular variation features for the last 12 500 years are 40° for inclination, 50° for declination, and a factor of 3 for intensity. The most powerful approach to obtaining accurate age determinations from lake sediments is multidisciplinary use of SV, radiocarbon dating and biostratigraphic studies. Work on Lake Winnipeg sediments began with a preliminary SV study of core 122 using a modification of this approach. A comparison between the paleomagnetic results obtained from Lake Winnipeg core 122 and the SV records from Elk Lake, Minnesota, and one available AMS date of 4040 ± 70 years BP was used to construct an age model. With an age estimate for the unconformity between Lake Winnipeg and Lake Agassiz sediments at site 122 at ~4000 years, the time-averaged linear sedimentation rate at the site was determined to be 0.105 cm/year. Additional multidisciplinary studies using SV curves and radiocarbon dating have since been used to determine ages of stratigraphic units and sedimentation rates at other sites within the lake (King et al., this volume).

COMPOSITIONAL ANALYSIS OF SEDIMENT

Compositional analyses of Lake Winnipeg sediments have been carried out by Last (1996), Henderson (1996), and Henderson and Last (1996; 1998). Samples collected at 10 cm intervals from the 1994 cores were analysed for a broad spectrum of parameters that include major and trace element concentrations, moisture content, organic matter and carbonate content, particle size, and bulk mineralogy. Both subtle and dramatic compositional and textural differences were noted regionally within the basin and, locally, between and within sedimentary facies. Within the Lake Winnipeg sequence, there is enrichment in organic matter and moisture content, Fe, Mn, P, V, and most other trace metals up the cores. With the exception of the northernmost cores, the carbonate content and Ca, Mg and Sr concentrations decrease upwards. In general, Lake Agassiz sediments have higher carbonate, Ca and dolomite contents than Lake Winnipeg sediments. The relative proportion of calcite, dolomite and the feldspars and concentrations of Ca, K, Mg, Na, Cr, Cu, and Sr are enriched in the North Basin of the lake in comparison to those of the South Basin. The proportion of clay minerals, organic matter content, and Mn, Ti, and V concentrations are elevated in the South Basin. These compositional variations appear to be related primarily to provenance, and/or diagenetic and anthropogenic controls. Two distinct mineralogical and geochemical associations were recognized. One, characterized by high carbonate, Ca and Mg content, calcite, and dolomite, can be associated with Paleozoic source terrane. The other is more complex. It is characterized by a high organic matter content, a high proportion of clay minerals, Al, Fe, and other trace metals, and may be associated with both the Mesozoic and Precambrian terranes, as well as certain diagenetic processes. Comparison with till geochemistry from the source areas indicates that sediments derived from the Mesozoic terrane are enriched in V and Zn. Compositional differences related to the various source terranes surrounding and underlying Lake Winnipeg have significant implications for estimations of the relative dominance of particular fluvial systems flowing into the lake basin during the Holocene, and for interpretation of the configuration of the ice sheet during various stages of deglaciation.

ISOTOPIC ANALYSIS OF SEDIMENTS, PORE WATERS, AND MICROFOSSILS

Research based on isotopic analysis of sediments and pore waters from Lake Winnipeg sediments has been directed by W. Buhay and R. Betcher (Betcher and Buhay, 1996; Buhay, 1996b; 1996a; Buhay and Betcher, 1996; 1998). For example, measurements of $\delta^{13}C$ (organic), $\delta^{13}C$ (cellulose) and carbon/nitrogen (C/N) ratios reveal 4 distinct zones in core 107. The lowest zone 1, is characterized by stable C/N values and $\delta^{13}C$ organic values that are 0.6 ‰ enriched over $\delta^{13}C$ cellulose values. The $\delta^{13}C$ cellulose values remain unchanged and there is an increase in C/N values that coincides with a 0.6 ‰ depletion in $\delta^{13}C$ organic values in zone 2. These changes may be related to physical differences in Lake Agassiz basin hydrology. For example, conditions such as water depth, wind driven mixing, climate, and influxes of groundwater may have promoted meromixis in the lake. Reduced or absent mixing between the upper and lower levels of the lake could have established an anaerobic bottom layer that promoted bacterial utilization of organic components richer in ^{12}C. This could explain the enriched $\delta^{13}C$ organic values during this lake stage. Lowering of lake level may have reduced the meromictic character of Lake Agassiz in favour of either a monomictic or diamictic form. In either case, improved oxygenation of bottom waters would promote removal of the more labile ^{13}C and N enriched organic components at the sediment/water interface resulting in the increase in C/N and depleted $\delta^{13}C$ organic values, evident in zone 2. Zone 3 is characterized by covariant $\delta^{13}C$ organic and $\delta^{13}C$ cellulose values that are essentially equal. The $\delta^{13}C$ (cellulose) values become progressively enriched in zone 3 while the corresponding C/N values decrease. The enrichment of $\delta^{13}C$ values during this lake stage could relate to elevated biological productivity, enriching the dissolved inorganic carbon pool in ^{13}C, in warmer lake waters, due to organisms utilizing more ^{13}C enriched HCO_3 due to the reduced warm water solubility of CO_2. In zone 4, divergence between $\delta^{13}C$ organic and $\delta^{13}C$ cellulose coupled with increased C/N values, may indicate the incorporation of allochthonous organic input at the core site due to shoreline regression as water levels receded to mark the end of Lake Agassiz.

The isotopic and geochemical composition of interstitial waters contained in tills and lacustrine sediments underlying Lake Winnipeg initially would have reflected the composition of the overlying glacial or lake (Agassiz and Winnipeg) waters during deposition. Subsequently, the composition of the pore waters in these sediments may have been modified by a variety of processes including expulsion during compaction, diffusion under concentration gradients, replacement by upward advection of underlying groundwaters, and aqueous and water-sediment geochemical reactions. By studying the current composition of these waters we may gain insights into the Late Pleistocene and Holocene geographic and climatic history of the lake and surrounding area and the processes that are taking place in the sub-lake environment today. In this study, pore waters were collected at 20 cm intervals from three cores collected in 1994. Two of the cores, 103 and 107, were collected in the north basin and one core, 115, in the south basin. Pore waters were analysed for stable isotopes (oxygen-18 and deuterium) and a suite of dissolved constituents. The waters were found to have retained an evaporative isotopic signature indicating they are original surface waters and have not been displaced by groundwaters from underlying bedrock aquifers. The degree of modification of the original pore water composition which may have occurred was been examined using a 1-dimensional advection-diffusion code.

Isotopic analyses also have been carried out on ostracodes. Samples from *Namao* cores 96900-205PC and 96900-206PC were wet-sieved in a 63 μm sieve and the residues examined for ostracodes (Rodrigues, 1996a). From 2 to 6 valves of *Candona subtriangulata* per sample were analysed for stable isotopic composition ($\delta^{13}CPDB$ and $\delta^{18}OPDB$) at the Stable Isotope Laboratory, Department of Geological Sciences, University of Michigan, Ann Arbor MI, under the direction of K. C. Lohman and L. Wingate.

The $\delta^{18}O$ ratios in the ostracodes record variations in the isotopic composition of Lake Agassiz bottom waters. A correlation with rhythmite thickness is evident with $\delta^{18}O$ becoming highly depleted in the thickest varves, suggesting these form during episodes of enhanced meltwater discharge.

PALYNOLOGY

Palynological investigations were conducted by Anderson and

Vance (this volume). Samples from three piston cores (103PC,106PC,105PC) recovered from offshore sediments in the north basin of Lake Winnipeg were processed to a) derive a composite pollen stratigraphy for Lake Winnipeg and underlying Lake Agassiz sediments and to correlate this pollen stratigraphy with dated pollen records on land, b) to determine vegetation and climate history for the basin as a whole, and c) to determine evidence for the annual deposition of rhythmites.

OSTRACODE MICROPALEONTOLOGY

Three ostracode zones have been recognized in Lake Agassiz and Lake Winnipeg sediments by Rodrigues (1996a; 1996b). Ostracodes are absent or present in low numbers mostly consisting of *Candona* spp. in the oldest of these, zone C. Zone B is subdivided into a lower B_2 interval and an upper B_1 interval. The lower, B_2, interval is characterized by congeners of *Candona* and *Lymnocythere*. The number of ostracode valves is lower and *Lymnocythere* is absent in the upper interval, B_1, where some of the valves are usually broken. Ostracodes are absent in zone A. The interface between the Lake Agassiz sediments and the Lake Winnipeg sediments recognized in acoustic data corresponds to the boundary between zones C and B. *Candona subtriangulata* is the major ostracode species in zone C, indicating relatively deep-water conditions, possibly as much as 200 m, during the deposition of the Lake Agassiz sediments. The presence of *Lymnocythere* spp. in zone B indicates shallower water depth.

THECAMOEBIAN MICROPALEONTOLOGY

Thecamoebians in Lake Winnipeg sediments were investigated by Burbidge and Schröder-Adams (1996a; 1996b; 1998). Thecamoebians are an informal classification of benthic testate protozoans that are found in mosses, soils, freshwater and some slightly brackish environments. Good faunal preservation under the acidic conditions common in lakes and bogs make this group an important paleolimnological tool. The thecamoebian content of sediments from three cores collected in Lake Winnipeg (Core 122A - South Basin, Core 110A - The Narrows, and Core 103 - North Basin) was examined. The Lake Agassiz sequence is barren of thecamoebians, whereas the overlying Lake Winnipeg sequence sediments contain abundant microfossils. In the South Basin three thecamoebian assemblages were distinguished. Species composition of the earliest assemblage indicates harsh environmental conditions in the South Basin possibly due to an initial brackish phase or low organic content of the sediments. This is followed by a highly diverse assemblage associated with a more favourable environment. The most recent assemblage is marked by a significant abundance increase and thecamoebian taxa tolerant of eutrophic conditions, perhaps indicating agricultural settlement. Holocene sediments at the north end of The Narrows (Core 110A) are characterized by two thecamoebian assemblages. The initial assemblage is of low diversity containing species tolerant of harsh environmental conditions. It compares with the earliest assemblage in the South Basin, but with less dominance of tolerant species. This is followed by the high diversity assemblage. Thecamoebian distribution in the North Basin is characterized by a mixed fauna that is less diverse than the more southern assemblages due to more restrictive environmental conditions. There is no indication of the initial harsh phase nor the more recent eutrophication evident in the South Basin. Lack of eutrophication in the more northern waters is attributed to lower population density.

ALGAL MICOPALEONTOLOGY

Both fossil and modern phytoplankton from Lake Winnipeg were examined by Kling (1996a; 1996b; 1998), while fossil diatoms were examined by J. Risberg (this volume). Recent phytoplankton and protozoan assemblages in Lake Winnipeg are spatially and temporally variable (Kling 1996a; 1996b; 1998). The main taxa are, however, similar throughout lake history. The lake has always been a diatom-bluegreen algae lake with Tintinnids and thecate amoeba forming significant components of the protozoan community. Comparison of changes in phytoplankton abundance and species composition of samples taken in 1923, 1969, 1992 and 1994 reflect a general trend towards increased eutrophication of Lake Winnipeg, particularly in the south basin.

Diatom analyses of core 103 (8 m), taken from the north basin of Lake Winnipeg in August 1994, indicate that diatom abundances are low throughout the core below 50 cm, except for a peak around 300-400 cm. Below 690-800 cm (Lake Agassiz) diatoms are virtually absent. *Stephanodiscus* and *Aulacoseira* are the two major pelagic diatom genera represented throughout lake history. Species changes near the top of the core indicate increased anthropogenic eutrophication. Shallow water littoral taxa were never abundant at this station. A progressive increase in abundance of planktic bluegreen algal remains (akinetes) from 600 cm depth to the top of the core indicates increasing phosphorus levels, warm temperatures and summer lake nitrogen limitation. Nitrogen fixing bluegreens (*Anabaena* and *Aphanizomenon* akinetes) and the diatoms (*Aulacoseira ambiqua, A. granulata, A. islandica, S. bingeranus*, and *S.*

niagarae) were abundant in the top sediments. These taxa, in addition to *S. agassizensis*, *Melosira varians* and *Cyclostephanos* dubius, are representative of present day plankton.

Freshwater diatom taxa were found to dominate with minor occurrences of indifferent to saline and brackish water taxa in samples from six sediment cores (northern basin) and 10 surficial samples (northern and southern basins) of Lake Winnipeg sediments. Chrysophyceae stomatocysts, phytoliths and sponge spiculae were relatively common. Diatom abundances were generally much lower than in adjacent Lake Manitoba. Barren sections typified glacial Lake Agassiz sediment.

ICE SCOUR

Sidescan sonar and high frequency seismic records obtained in Lake Winnipeg in 1994 and 1996 show numerous linear furrows in the soft sediments of the lake bottom that generally trend NNW-SSE, similar to the orientation of prevailing winds in late winter and spring (McKinnon, 1996; McKinnon et al., 1996, this volume). These features are up to 2 m in depth, 200 m in width, and several km in length, and are in many cases flanked by berms about 0.5 m in height. The furrows show crosscutting relationships, changes in orientation, and abrupt terminations. Lake bottom outcrops of Lake Agassiz sediments are heavily scoured, with a complex pattern of scour orientation, suggesting that furrows inscribed into softer Lake Winnipeg sediments are obliterated more rapidly than is the case in the harder Lake Agassiz sediments. The geometry and distribution of these features, and general knowledge of the regular formation of pressure ridges in the lake ice, indicate that wind-driven pressure ridge keels dragging on soft bottom sediment form these features. Furrows are particularly prevalent in the southern South Basin and in northwestern North Basin, where ice-accumulation conditions and water depth appear to favour scouring. Dual frequency sidescan records obtained in 1996 indicate that the majority of the scours are slightly buried, being apparent on a low-frequency record but not on the high frequency record, indicating that some years have passed since formation of most of the features.

Another type of feature occurring in the sidescan sonar records are dark linear features with diffuse edges, up to 15 m in width and several hundred metres in length. These features show neither trough nor berm on high frequency seismic reflection records, but a strong reflector at the lakefloor masks the record beneath the feature. Similar features observed on the Lake Ontario lakefloor have been referred to as linear acoustic backscattering anomalies (LABAs), and a pattern that radiates from the Welland Canal, combined with coal or crushed stone in bottom grabs, indicates that the features are debris trails associated with shipping. It is not known whether a similar genesis applies on Lake Winnipeg.

GRAVITY AND UPLIFT

North America has experienced differential crustal uplift due to the delayed response of the Earth to the surface unloading caused by the decay and collapse of the continental ice sheets. Although other factors such as climate have influenced the evolution of Lake Winnipeg, it appears that uplift has been a persistent control. Although this may have been the case in the past, a major question is whether it is the case today. Studies of the rate of coastal submergence in recent centuries (Nielsen, 1998) and lake-gauge studies (e.g. Tackman et al. 1998) have provided indications of ongoing uplift. Determining with greater confidence the past and present rate and direction of tilting will, however, assist understanding of both the history and evolution of Lake Winnipeg, and the ongoing processes that will affect future evolution of the lake. To date, the pattern of uplift due to isostatic rebound has been determined largely by measuring the elevation of relict marine and glaciolacustrine shoreline features that contain ^{14}C-datable material. These studies are continuing to provide new evidence in the form of isobase maps and regional tilt profiles that put new constraints on the history and evolution of the Laurentide sheet. Historical lake level data and repeated high-precision geodetic measurements contribute additional constraints that must be accommodated by a unified postglacial rebound model. A major initiative that will advance this topic through measurement of absolute gravity and uplift is being co-ordinated by A. Lambert, N. Courtier and T. James of GSC-Pacific (Lambert et al., 1996; Lambert, 1996; Lambert et al., 1998, this volume). This five-year project started in 1996 and is a co-operative effort by GSC, Manitoba Hydro, the US National Aeronautics and Space Administration (NASA), the US National Oceanic and Atmospheric Administration (NOAA), and Geomatics Canada.

Two new continuously-operating GPS receivers have now provided three years of GPS data recorded by GSC. In June 1996, equipment was installed at a site near Flin Flon made available by the Department of National Defence. In October 1996, another station was installed at the Underground Research Laboratory near Lac du Bonnet, a facility of the Pinawa-based Whiteshell Labs of Atomic Energy of Canada Ltd. The GPS receivers, ROGUE SNR-8000's, were obtained on long-term loan from NASA under the Solid Earth and Natural Hazards Program. Construction of buildings, antenna monuments, data communication equipment, and uninterruptible power supplies were carried out by GSC with funding from Manitoba Hydro. Data from these two stations are transmitted every four hours by automatic telephone dial-up to GSC Pacific. The data are preprocessed and archived, are also acquired by the Geodetic Survey of Geomatics Canada, and are reformatted and retransmitted to the NASA Crustal Dynamics Data Information System. It is intended that these GPS receivers will be operated at these stations for a period of five years in conjunction with existing GPS receivers at Churchill and the North Liberty station near Iowa City, Iowa. These data will permit a joint analysis of vertical movement rates, in combination with data from Churchill, provided by Geodetic Survey of Canada, as well as from North Liberty, Iowa, provided by Jet Propulsion Laboratory, Pasadena, and other North American reference stations. Analysis of daily baselines among the four mid-continent stations and other selected GPS receivers in Canada and the USA will be carried out to determine the relative vertical and horizontal crustal velocities for comparison with theoretical model predictions. Churchill and North Liberty are stations participating in the International GPS Service for Geodynamics (IGS) program. Highly automated GPS data processing software, the Bernese processing engine, has been installed at GSC Pacific and is now being used to analyse the existing backlog of data. Initial GPS estimates of crustal movement rates should be available by mid-1999.

High-precision gravity measurements have been made by GSC and NOAA at Churchill and International Falls, Minnesota since the late 1980s and, in association with the Lake Winnipeg Project, at new stations in the intervening area since spring 1995, using FG5 absolute gravimeters. At Churchill, eight years of data indicate a steady decrease in gravity at a rate of -1.45 ± 0.19 mGal/yr. All of the gravity data collected at six high-precision stations are being reanalysed using a common data analysis protocol developed by GSC and NOAA. It has become better appreciated recently that the vertical gravity gradient at many sites departs significantly from linearity, a significant factor when measurements made by different instruments at different heights are reduced to the standard international height of 1 m. Consequently, the vertical gravity gradients at Churchill, Flin Flon, Pinawa, International Falls, Wausau (Wisconsin) and Iowa City were remeasured. The new vertical gravity profiles should keep the vertical transfer uncertainty to less than 1 mGal, the precision of the absolute measurements themselves. Care has been taken to ensure that no unexpected biases arise in the Canadian FG5-106 gravimeter with respect to the US FG5-102 instrument. Measurements are made every year with the Canadian instrument at the Table Mountain Geophysical Observatory near Boulder, Colorado, the home base for the US instrument, prior to each measurement campaign on the mid-continent line. A pattern of decreasing gravity in the north, corresponding to uplift, and increasing gravity in the south, corresponding to subsidence, is emerging from preliminary results.

By 2001, the GPS and absolute gravity data are expected to provide rates of change accurate enough to constrain postglacial rebound models significantly better than present modelling.

SHORE PROCESSES

Research on shore processes is being directed by D.L. Forbes of GSC Atlantic (Forbes and Frobel, 1996; Forbes 1996; Forbes, this volume (Section 9.5)). The work has included reconnaissance surveys in 1994, targeted investigations in 1996, surveys and sampling on the lake ice in March 1997, and a month-long intensive effort in September 1997. Basic information on many aspects of Lake Winnipeg shoreline processes was unavailable when this new program of cooperative research was launched. Little was known of shore-zone characteristics and processes in the North Basin and central lake, while only limited information was available for the South Basin. This lack of data fostered public apprehension concerning the effects of lake-level regulation on shoreline stability, and compromised efforts to identify the causes of shoreline erosion. A general understanding of shore system processes is required in order to ensure effective and integrated shore-zone and lake basin management.

The lakeshore can be described in terms of seven shore-type associations: 1) marsh and deltaic shores; 2) low-energy Precambrian bedrock outcrop with discontinuous marsh; 3) sand-dominated beaches, spits and barriers; 4) heterogeneous sequences of sand or gravel beaches, low scarps, and rock or boulder-lag headlands; 5) gravel beaches and barriers associated with sedimentary rock cliffs; 6) unlithified bluffs or unstable slopes with associated mixed beaches; 7) artificially modified shores. Shore type is a function of substrate geology, basin morphology, lake level, wave climate, sediment supply, and the action of various shore-zone processes over time. Resistant Precambrian rocks with limited sediment cover dominate the eastern lakeshore. Ordovician sedimentary rocks outcrop along the western and southeastern shores, with a variable cover of glacial, glaciofluvial, and glaciolacustrine sediments.

The major achievements of the 1994 shoreline survey included: 1) twelve hours of low-level oblique video imagery covering most of the mainland lakeshore and major islands; 2) voice commentary describing visual observations and oblique air photos supplementing the video; 3) shore surveys and sampling carried out at 12 sites around the lake; 4) development of a shore-type classification for Lake Winnipeg; 5) the first comprehensive mapping of physical shore-zone characteristics for the entire Lake Winnipeg shoreline; and 6) preliminary interpretations of lake-level history from geological evidence in the shore zone.

A number of major questions concerning lakeshore processes in Lake Winnipeg remained after or grew out of the 1994 reconnaissance, including: 1) the origin and evolution of large lakeshore sand deposits; 2) sediment transport rates alongshore and offshore in relation to shore erosion and shoreface profile adjustment; 3) the role of frazil-, slush-, and anchor-ice sediment transport during freeze-up, of ice piling and lake-bottom scour during winter and spring, and the time-variability of these processes; 4) the character of waves on Lake Winnipeg and their relationship to meteorology and basin geometry; 5) the role of wind-driven water level fluctuations in erosion and cross-shore transport; 6) shoreline erosion rates; 7) the influence of shore structures on erosion; 8) long-term variability of storminess, lake levels, and wave energy, including evidence for extreme lake level events; and 9) evidence for long-term lake level change, both basin-wide and tilting, and the shoreline response as a function of shore type, shoreface morphology, geology, and exposure.

These issues were pursued in association with the *Namao* cruise of summer 1996. Because a full understanding of shoreline processes requires knowledge of shoreface sediments extending out into the basins, close collaboration was maintained on the planning of geophysical survey lines and coring targets for the offshore survey, to address objectives of both programs. Extension of the CCGS *Namao* cruise by one week enabled nearshore surveys directly serving shoreline process research to be carried out. The shore-zone surveys were conducted from a 20-foot aluminum work boat capable of a speed of 33 knots under ideal conditions, but slow and exposed in rough weather. The work boat operations were highly successful, completing 128 geophysical survey lines at 17 sites, a total of 202 km of data including bathymetry and sub-bottom reflection data profiles and sidescan sonar imagery. Onshore surveys were completed at 11 new sites and 14 benchmarks were installed. In total, 27 grab samples of lake-floor sediments were obtained from the work boat and 33 samples of beach, dune, and cliff deposits were collected onshore.

Key information on shoreface profiles and sediments also was obtained by sounding and coring through the ice in early 1997. This program targeted a number of profiles previously surveyed in the 1970s as well as other sites where boat or ship support was not available to extend shore-based surveys offshore. Ice-based coring was also undertaken in marshes and other sites not readily accessible for coring during the summer season. The winter program provided an opportunity to observe surface features of the lake ice cover, including pressure ridges and shore-ice rideup or pileup. Ice cores were examined for evidence of sediment inclusion by frazil or other processes, revealing localized particulate concentrations as high as 17.2 g/L. Radarsat and other satellite imagery is also being used to analyse lake ice processes.

The field effort in September 1997 had two major components, one consisting of detailed lakebed surveys, and the other focussing on nearshore dynamics and erosion processes. The combined program operated from the Coast Guard search-and-rescue (SAR) base in Gimli and used two work barges supplied from the Coast Guard base in Selkirk, the *Namao* landing barge and the Selkirk base barge. For the survey program, a geophysical lab was constructed to fit inside the *Namao* barge, from which bathymetric, sidescan sonar, and high-resolution seismic reflection surveys were carried out in the western South Basin. This part of the project replicated many components of the ship-based geophysical surveys of 1994 and 1996, but provided a means of carrying the lakebed mapping into very shallow water. The survey also covered areas of the central basin where ice ridging was observed the previous winter, as well as regions of known ice pileup in the shore zone during the 1996-1997 ice season. Extensive scouring of the lakebed was recorded in previously unsurveyed areas and work is in progress to determine whether any of the newly documented scours correlate with observed ice features. Sidescan sonar mosaics were completed over the shoreface off Willow Point, the site of a nearshore dynamics and erosion study, and north of Gimli. The surveys also documented outcrops of erosion-resistant glacial deposits and helped to correlate different parts of the lakebed sediment sequence to sections in the shore cliffs. This provided a basis for analysis of shore erosion as a function of nearshore sediment type and stratigraphy.

The nearshore dynamics and erosion process study used the Selkirk base barge, modified to carry a small Hyab crane. This provided support for deployment of two recording InterOcean S4A wave and current meters, and a custom-built instrumented tripod known as Ralph. The latter carried four EM current meters providing current velocity profiles, a pressure transducer for wave and water level measurements, and an acoustic backscatter sensor for measurement of bottom scour and suspended sediment profiles. These instruments were in place for 2 weeks and recorded three moderate storms. Complementing the moored instruments, numerous drops of a rotating sonar head were completed, giving high-resolution images of the lakebed before and after storm events. This revealed the formation and reworking of sand and gravel ripples over parts of the clay erosion surface, demonstrating that abrasion by coarse sediment under moderate storms is a factor in the shoreface erosion process. The sonar surveys also revealed a hummocky, pitted, and scoured clay surface, consistent with earlier sidescan and bathymetric data and with SCUBA observations. The SCUBA program was also intended to provide geotechnical data on shear strength, compressive strength, bulk density, fracture characteristics, and microtopography, as well as direct measurements of erosion. These efforts largely failed because of the zero visibility in the lake. Despite these problems, valuable and previously non-existent data on wave dynamics, sediment transport, erosional morphology, and fracturing characteristics in the nearshore of Lake Winnipeg were obtained. These provide a basis for establishing erosion thresholds related to abrasion and entrainment of fractured clay on the shoreface.

Thus the following objectives were accomplished during the 1997 work: 1) additional lakebed surveys in the South Basin to fill gaps in our knowledge of shore-zone bathymetry, nearshore sand and gravel distribution, limits of exposed Lake Agassiz clays, and shoreward limits of Lake Winnipeg basin muds; 2) preliminary study of erosion processes on nearshore profiles cut into relict Lake Agassiz clays, including quantitative data on shoaling waves, nearshore currents, bottom boundary dynamics, nearshore lakebed morphology and roughness, sediment transport, and lakebed erosion; 3) further investigation of shoreline deposits recording environmental changes on Lake Winnipeg; 4) further analysis of survey data and imagery for formation, location, and dynamics of ice ridging; and 5) lakebed surveys of previous survey lines and areas of observed pressure ridges and shore ice pileups in winter 96-97 to estimate frequency of new ice scours.

Lake-level variation at time scales of greater than one year can be divided into tilting due to differential uplift (lake level stable at the outlet and rising at a rate increasing with distance south of the outlet) and basin-wide adjustments of climatic and hydrologic origin. Lake-level rise is clearly indicated by transgressive beaches and barriers in the South Basin, such as Willow Point, Netley Marsh and Grand Marais, among other evidence. Along the north shore of the lake near the outlet, a well-developed arc extending from feeder bluffs in the east to the 20 km Limestone Point spit in the west reflects prolonged exposure to long-fetch southerly waves at relatively constant effective lake level. However, submerged ridges behind Limestone Point, transgressive sandy barriers with dunes along the eastern shore of the North Basin, transgressive gravel structures along the western shore, washover deposits in Sturgeon Bay and Fisher Bay, complex structures of the large Disbrowe Point spit near Berens River, and other indicators, imply a component of medium- to long-term basin-wide submergence. Weathered high-level beaches at sites such as Selkirk Island and along the western shore of Sturgeon Bay suggest water levels above that of the present, due either to major storms, or temporarily sustained higher water levels. Taken together, these observations support the notion that Lake Winnipeg is expanding. It is important to note that erosion is active not only in the South Basin, but also at the north end of the lake.

WAVES

An adequate account of deep water and nearshore wave climate is fundamental to offshore and coastal engineering. It commonly is not, however, cost effective or practical to obtain wave data for each application. Long-term statistics are required for structural design, so short-term observations are of limited use. Wave climates therefore tend to be modelled using meteorological data. These models require calibration and testing, however, and an opportunity to do so was presented by the Lake Winnipeg Project. During summer 1996, under the direction of J. Doering and D. Fuchs of the University of Manitoba, a north-south array of three Waverider buoys was deployed in the South Basin. Two 0.7-m nondirectional Waveriders were deployed from June 13 to October 27, inclusive, although several weeks are missing from the north buoy due to malfunction. One 0.9-m directional Waverider was deployed from September 13 to October 27, inclusive. Data were transmitted to a shore station at Grand Beach. A north-south arrangement was chosen because storm winds over Lake Winnipeg tend to originate from a northerly direction. The synoptic array has allowed comparison of predicted and observed wave conditions, including examination of wave growth to the extent that the frequency response of the buoys allows.

Meteorological data, including wind speed, direction, and maximum gust, water and air temperature, and barometric pressure, have been obtained from the Environment Canada buoy near the northern Waverider buoy, from Gimli, and also from Victoria Beach. Energetic conditions occurred at the meteorological buoy on 13 of the 62 days of record, when wind speed exceeded 40 km/h, and 55 days had wind speeds over 30 km/h. For the Gimli station, 9 days had wind speeds over 40 km/h and 41 days had wind speeds exceeding 30 km/h. For the Victoria Beach station it was found that 34 days had wind speed readings that were in excess of 40 km/h and 65 days had readings exceeding 30 km/h.

The model SWAN (Simulation of WAves in the Nearshore) developed by Holthuijden is currently being used to construct a model for significant wave height, peak period, and wave direction that will then be compared to the observed values at the three buoys (Fuchs and Doering, 1999). Variance density and directional spectra are also being compared at each buoy. A comparison of Gimli weather data with Victoria Beach is being used to examine the effect of spatial variance on the wind field during storms. The model will then be applied to hindcasting wave climate on the lake for selected storms, as well as modelling wind conditions at various lake elevations. Future work may involve the modelling of nearshore wave conditions, and use of SWAN model output to develop a sediment transport model for the South Basin. Over-water meteorological measurements will also be used to examine, and remove if necessary, the influence of atmospheric stability on wave growth. Meteorological data will be used to predict deep water wave height, periods and direction. A model developed for a previous Lake Winnipeg project, based on the wave height, period, and direction, will also be used to predict deep water conditions.

LIMNOLOGY

In order to map the texture and composition of bottom sediments, in particular the analysis of several variables not addressed by the 1969 Freshwater Institute survey, a systematic set of bottom sediment samples was collected in 1994. Prior to the cruise, 50 evenly spaced target sites were designated, with a more dense sampling grid in the South Basin. A total of 33 of the stations were occupied from the ship's launch. Positioning was determined using a portable GPS unit. An intact bottom sediment sample was recovered using a Ponar dredge or, in a few cases, an Eckman dredge. Opening of the dredge permitted the intact sample to be placed in a plastic pan in the boat. A one-litre sample was recovered from sediments within 5 cm of the sediment-water interface. This activity was assigned the lowest priority of the geological objectives. No samples were obtained at times when wave conditions prevented safe use of the launch. No sampling was done from the ship, in order to avoid interference with coring operations. Although 33 sampling stations were occupied, only 31 bottom sediment samples were obtained. At two stations, a hard lake bottom was encountered, and no sediment was recovered. Air temperature, surface water temperature, and a Secchi disk measurement were recorded at all 33 sampling sites. Conductivity-temperature-depth (CTD) profiles, including data from below the sediment-water interface where bottom sediments were soft, were only taken at 24 of the sites, due to the necessity that the equipment be transferred to another Freshwater Institute project prior to the last two days of sampling. CTD profiles were also taken from *Namao* during the 1996 cruise, using GSC equipment.

During both cruises, phytoplankton samples, consisting of 0.25 litre of surface water treated with a preservative, were regularly collected. Zooplankton net hauls also were obtained, and results were reported by Salki (1996). Excess dredged sediment remaining after bottom sediment samples were taken in 1994 was screened in order to recover benthic organisms, which were preserved in formaldehyde. Time constraints prevented quantitative recovery, although qualitative analyses were reported by Cobb (1996). A few trawls to net pelagic fish along offshore transects were attempted, but were unsuccessful.

Water samples were taken during both the 1994 and 1996 cruises. Subsamples, collected for dissolved silicon and dissolved organic carbon analyses, were placed in 100 ml jars containing a preservative. Additional subsamples were filtered on board for the determination of chlorophyll and particulate silicon, carbon, nitrogen, and phosphorus. Samples were also taken for measurement of CO_2, and an instrument that allowed continuous monitoring of CO_2 was operated for a portion of the 1996 cruise. Results are on file at the Freshwater Institute, under the direction of M. Stainton.

CONTAMINANTS

A program of contaminants research based on analysis of bottom sediment samples, box cores, and long cores collected from the CCGS *Namao* during the 1994 cruise is being conducted at the Freshwater Institute (Lockhart, 1996; Lockhart et al., 1996; this volume). The principal topics are radiochemical dating of recent sedimentation rates, and the concentrations of toxic metals in the sediments. The work is being co-ordinated with similar work on the Red River by the United States Geological Survey (Brigham, 1996), and work on organic contaminants at the University of Winnipeg (Fisher-Smith and Friesen, 1996).

Box core subsampling was conducted on board the *Namao* in 1994 by L. Lockhart. When a filled box corer was returned to the deck of the ship, the top of the apparatus was removed to expose the surface of the sediment. Cores 10 cm in diameter and 30-50 cm in length were then taken by pushing core tubes into the top of the sediment column with gentle vacuum to minimize compression of the sediment. The cores were extruded using a Teflon plunger and sliced into 1 cm thick samples. As sediment emerged from the tube into a clear plastic ring made of the same material as the core tube, slices were cut off with a stainless steel slicer. The samples were placed in Whirlpak bags and refrigerated until transferred to the Freshwater Institute after the ship reached Selkirk. Samples were then stored in a cold room at 4 °C prior to subsampling and freeze drying. Subsamples were supplied to a number of other investigators, notably W.M. Last, W. Buhay, H. Kling and S. Burbidge. The sediment samples were freeze dried, subsampled, and digested with nitric, perchloric, hydrofluoric and sulfuric acids in Teflon beakers. Final volumes were adjusted to 25 ml. Several metals were analysed by flame atomic absorption spectroscopy. Cadmium was analysed by graphite furnace atomic absorption and mercury by cold vapour atomic absorption. Samples analysed for mercury required a separate digestion with aqua regia. National Research Council of Canada standard reference sediments were analysed concurrently as a measure of analytical quality.

The distribution of metals in the sediments showed higher levels of mercury, cadmium and lead in the South Basin than in the North Basin. This may result from the different geological settings of the two basins, and/or anthropogenic input to the South Basin from the Red River and Assiniboine River may be responsible. Among the bottom grabs collected in 1994, mercury levels in the nine samples from the North Basin ranged from 28 to 70 ng/g dry wt with a mean of 52 ng/g, those for the narrow, central part of the lake ranged from 34 to 100 ng/g with a mean of 63 ng/g, and mercury levels in the South Basin were generally higher, the range being from 75 to 161 ng/g dry wt with a mean of 126 ng/g (Lockhart et al., 1996). Statistically, the South Basin mercury levels exceeded those in both the central and north parts of the lake ($p < 0.001$). Given the higher levels in the South Basin, the question is whether the difference is caused by pollution or by the geology of the basins. A long core was taken west of Gimli (site 122) and a short box core was taken nearby (site 116). Taken together, these two cores appear to offer an historical record of mercury concentrations starting from the present time at the top and extending back several thousand years. Mercury was analysed in 10-cm segments of the long core and values for all segments below 30 cm fell in the range of 29-61 ng/g dry wt. The top three segments showed striking elevations with mercury levels increasing to 116 ng/g at the top. The short core from the location nearby was analysed for lead-210 and cesium-137 activities that permitted calculation of a sedimentation rate of 1000 g/m^2 yr. Mercury at the top of this core was 129 ng/g, which yields a flux of 129 mg/m^2 yr. If the sedimentation rate calculated for the short core is applied to the long core, then the flux at the base of the long core would be about 33 mg/m^2 yr. This approach suggests that mercury inputs to the South Basin have increased about 4-fold over several thousand years.

Work on the application of stable lead isotope analysis to determination of the source of lead in Lake Winnipeg sediments is being conducted by S. Burbidge et al. (this volume). Stable lead isotope compositions were determined for nitric acid-soluble and residual sediment fractions of sediment samples from a north-south transect. Results show that lead in Lake Winnipeg sediment is derived from natural as well as anthropogenic sources and both interbasinal and vertical variations in source material can be distinguished. The natural source lead in Lake Winnipeg sediments is predominantly derived from the Superior Province, on the basis of a model age of 2.5 Ga. North Basin sediment is characterized by highly radiogenic acid-soluble lead and relatively non-radiogenic residual lead derived from high radiogenic lead/common lead Archean granitic rocks of the Superior Province. Lead in South Basin sediments is largely derived from Paleozoic and Mesozoic sedimentary rocks, which have a more radiogenic common lead component originally derived from the Superior Province. Vertical variations in lead isotope composition indicate three phases of lead input in Lake Winnipeg: 1) highly radiogenic Lake Agassiz sedimentation; 2) relatively constant isotopic compositions of natural Lake Winnipeg sources, and 3) reduced isotopic ratios of acid-soluble anthropogenic lead. Specific sources of anthropogenic lead for Lake Winnipeg can not be determined with the present data since the anthropogenic isotopic composition is unknown.

During the 1994 cruise, ten air sample transects were taken using a Grasby GMW high-volume air sampler mounted at the bow of the *Namao*, and 20-litre water samples were taken for the investigation of trace organic contaminants (Fisher-Smith and Friesen, 1996). The air sampler was fitted with a glass-sampling head consisting of two filters in series, a glass fibre filter with a pore size of 1 mm followed by a three-inch long plug of polyurethane foam. The glass fibre filter was used to trap persistent organic contaminants that are sorbed to particulate matter with a diameter of 1 mm. The polyurethane foam provided a trap for volatile and semivolatile organic contaminants that exist in the vapour phase. Due to the low concentrations of the target organic contaminants in the air and water, it was necessary to sample large volumes of both matrices to ensure sufficient material for detection. The high-volume air sampler was, therefore, in use for as long as possible during each day of the cruise. Sampling was restricted to slow cruising speed and to times when prevailing winds carried the ship's exhaust away from the air sampler. During air sampling, wind speed and direction, air temperature, and atmospheric pressure were recorded at regular intervals. At the end of a sampling period, the filter and foam plug were placed in cleaned glass containers and frozen. A total of twelve samples were pumped into pre-cleaned stainless steel transfer tanks using a submersible pump. The tanks were stored in a cooler on board to maintain a temperature of 2-8° C to preserve sample integrity.

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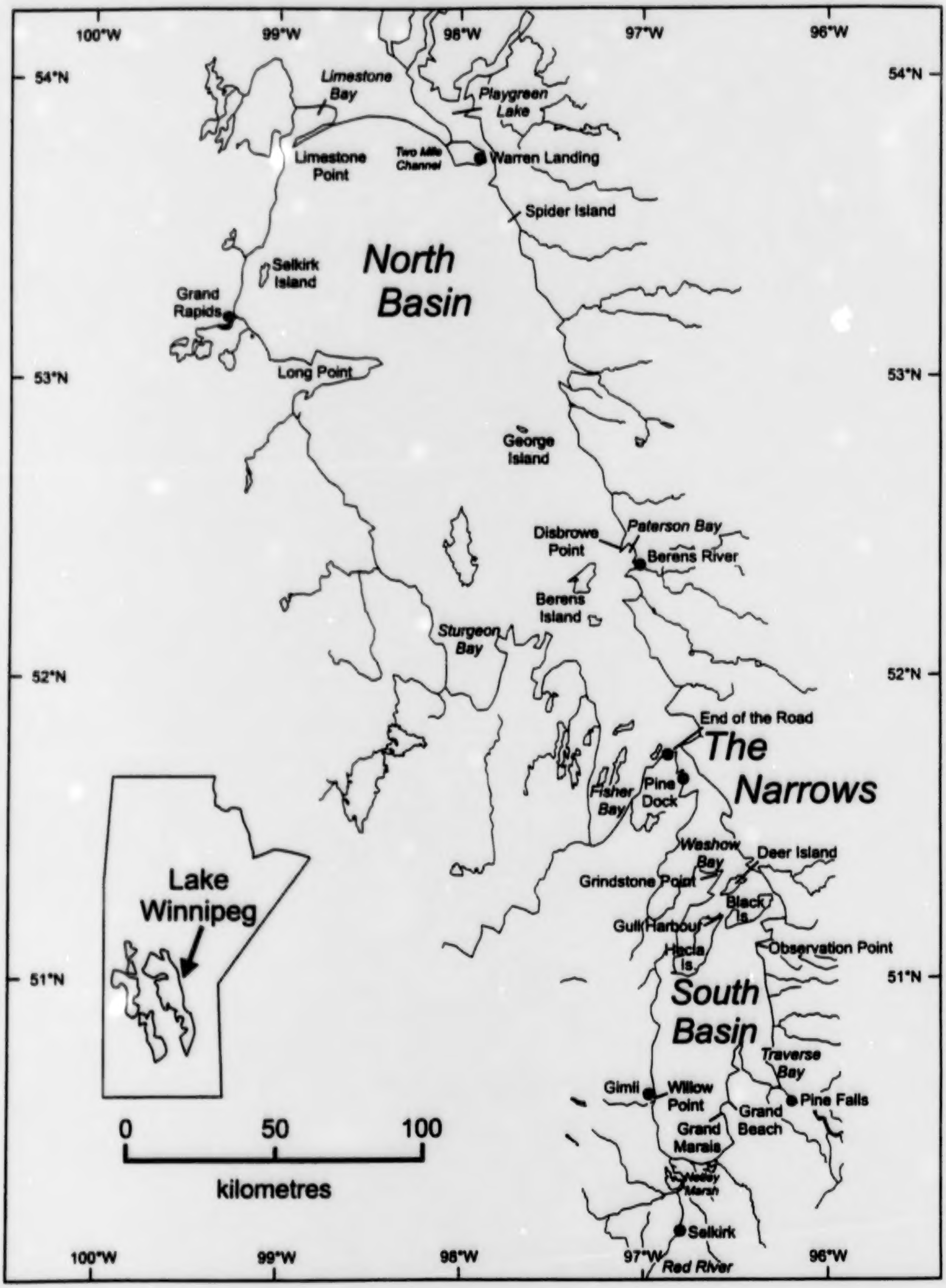
100°W
99°W
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97°W
96°W
54°N
53°N
52°N
51°N
Limestone Bay
Playgreen Lake
Limestone Point
Two Mile Channel
Warren Landing
Spider Island
North Basin
Selkirk Island
Grand Rapids
Long Point
George Island
Paterson Bay
Disbrowe Point
Berens River
Berens Island
Sturgeon Bay
End of the Road
The Narrows
Fisher Bay
Pine Dock
Washow Bay
Deer Island
Grindstone Point
Black Is.
Gull Harbour
Hecla Is.
Observation Point
South Basin
Traverse Bay
Gimli
Willow Point
Pine Falls
Grand Beach
Grand Marais
Netley Marsh
Selkirk
Red River
Lake Winnipeg
0
50
100
kilometres

Figure 1. Lake Winnipeg location map.

2. Introduction

2. Introduction

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2.1 1994 survey

In 1994, the Geological Survey of Canada (GSC) and Manitoba Energy and Mines (MEM), with the support of Manitoba Hydro and several cooperating agencies, carried out Phase I of the Lake Winnipeg Project. The objectives of that project were as follows:

1. Determination of postglacial history, with emphasis on natural lake level change, evolution of shoreline features, and sedimentation patterns ranging from Lake Agassiz to the influence of economic development on sedimentation and nutrient supply over the past century;
2. production of maps and subsurface models integrating onshore and offshore Quaternary, Paleozoic, and Precambrian geology;
3. hydrogeology, specifically the search for areas of groundwater discharge; and
4. water chemistry and associated work on planktonic and benthic biota.

Previous to this work, knowledge of Lake Winnipeg geology was limited to the collection of bottom samples and the identification of basins of sediment accumulation. Field work in 1994 was carried out as a four-week cruise aboard the Canadian Coast Guard Ship (CCGS) *Namao*, followed by a 10-day shoreline survey. Geophysical instrumentation on the cruise included satellite navigation, seismic reflection, sidescan sonar, ground-penetrating radar, and magnetometer. Geological sampling was carried out using a piston corer, gravity corer, box corer, and grab samplers. Limnological and biological sampling were also carried out, using equipment supplied by the Freshwater Institute of Fisheries and Oceans Canada in Winnipeg.

Phase I of the Lake Winnipeg Project, the first comprehensive geological survey of the Lake Winnipeg basin, produced many fundamental insights into the structure and evolution of the basin. The project is fully documented in Geological Survey of Canada Open File report 3113.

Highlights of Phase I of the project include:

1. the establishment of a network of scientific experts with up-to-date insight into all aspects of the Lake Winnipeg physical and biological environment;
2. major revisions regarding the assumed extent of bedrock types and thickness of sediments under the lake;
3. acquisition of data which supports the view that Lake Winnipeg is migrating southward in response to tilting of the basin;
4. a shoreline survey that provided a classification of Lake Winnipeg shoreline types confirmed the transgressive character of the South Basin shore, and also significantly influenced thinking by drawing attention to the transgressive character of the North Basin shore;
5. recognition of extensive scour of the lakefloor by present-day ice pressure ridges; and
6. acquisition of data providing the first limnological and biological overview of the lake since 1969.

A major enhancement of the Lake Winnipeg-related effort has been the geodynamics initiative which was begun in 1995 by the GSC due largely to support from Manitoba Hydro. This program of absolute gravity measurements and long-term Global Positioning System (GPS) monitoring of crustal motion will provide a valuable independent view of the tilting which seems to be affecting Lake Winnipeg.

2.2 1996 survey

In late 1995 and early 1996, scientists involved in the planning and execution of Phase I of the Lake Winnipeg Project proposed that Phase II be conducted during the summer of 1996, for the following reasons:

1. scientists who participated in the 1994 cruise were well-prepared to plan and execute a focussed, productive follow-up survey;
2. whether a Coast Guard ship of suitable size would be available on Lake Winnipeg in future years was

in doubt; and

3. a second cruise would contribute significantly to an enhanced understanding of priority issues including the southward migration of the lake and scouring of the lake floor by ice.
4. a second cruise would provide a logistical base for implementing the first of a two-year study of shore processes and ice scouring, Phase III of the lake Winnipeg Project.

Endorsement of the project by Manitoba Hydro, the Province of Manitoba, the GSC Industrial Partners Program, and the Canadian Coast Guard resulted in confirmation of a second ship-based survey.

The 1996 survey featured a reduced emphasis on biological and limnological sampling and an increase in near shore surveys. These shoreline surveys at specific sites were completed to link offshore and onshore geology. As well, directional and nondirectional wave rider buoys were placed in the South Basin of the lake to provide wave climate information; this work is being done in cooperation with the University of Manitoba.

The scientific cruise, designated *Namao* 96-900, on board the CCGS *Namao* began with mobilization of the ship at the Canadian Coast Guard Base in Selkirk, Manitoba from August 6-8 (corresponding to Julian days 219 to 221). The geophysical survey phase began on August 9 in the South Basin (Day 222) and was completed on August 21 in the North Basin (Day 234). Following the geophysical survey phase, the geological coring phase covered the lake from north to south starting on August 22 (Day 235) and ending on September 3 (Day 247). Demobilization of the ship took place in Selkirk from September 4-6 (Days 248-250). Near shore surveys utilizing the ship's launch, and limnological sampling from the CCGS *Namao* were undertaken during both the northbound geophysical phase and the southbound coring phase of the cruise.

The CCGS *Namao* was operated under the direction of Captain Rob Aitchison; the officers and crew of the vessel ably assisted in the survey and sampling. The vessel was built in 1975 at Riverton Boat Works, Riverton, Manitoba as a navigational aids tender. The ship is 33.5 m in length, 8.5 m in width and has a draft of 2.1 m. On-board berths were available for four of the scientific staff in an accommodation trailer welded to the deck for that purpose; other members of the scientific staff slept in various locations on the ship, or onshore in tents or Coast Guard buildings. Todd and Lewis remained on board for the duration of the cruise to provide continuity between the geophysical survey and the geological coring. Todd directed the geophysical survey and Lewis directed the coring. Forbes and Nielsen directed the near shore survey work using the ship's launch; Douma coordinated the navigation and geophysical equipment setup on the launch. Asprey, Burns, Chapman and Girouard contributed to coordination of the geophysical survey phase; Jodrey coordinated the coring with assistance from Asprey and Chapman. Thorleifson was responsible for limnological sampling. Todd, Lewis and Thorleifson spent August 31 to September 2 (Days 244-246) undertaking a trial geophysical survey on Lake Manitoba with the assistance of Coast Guard personnel and in cooperation with Dr. J.T. Teller of the University of Manitoba.

2.3 Report format

This Open File Report provides both a cruise report of activities on Lake Winnipeg in 1996 and preliminary scientific results. The cruise report (Section 4) is intended to provide a record of day-to-day activities on board ship, an overview of technical aspects of the equipment used, and a summary of geophysical and geological data obtained during *Namao* 96-900. Preliminary interpretations of the geophysical and geological data follow in Sections 5 to 9. In the following narrative account of the day-to-day activities (Section 4.1), reference is made to instrumentation and data which are fully described in later sections of the report.

Hereafter in the cruise report, monthly days are accompanied by their corresponding Julian days. In the narrative account of the cruise (Section 4.1), time of day is given as local ship time, i.e. Central Daylight Time (CDT). Elsewhere, logged times are given as UTC (Universal Time Coordinated) which, for Lake Winnipeg, is five hours more advanced than CDT. Thus 1200 hours ship time (CDT) is 1700 hours UTC.

3. Acknowledgments

3. Acknowledgments

B. J. Todd

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The success of Phase II of the Lake Winnipeg Project is a result of enthusiastic cooperation among people from a suite of institutions. Foremost was the effort made on board the CCGS *Namao* by staff of the GSC: Ken Asprey, Rob Burns, Borden Chapman, Marten Douma, Paul Girouard and Fred Jodrey. Funding for Phase II was provided by the Geological Survey of Canada and Manitoba Hydro. The support and guidance of management teams at the Terrain Sciences Division of the GSC, and at GSC Atlantic is acknowledged. Manitoba Hydro endorsed the project at its initiation in 1994 and continued their support through 1996. Interest and guidance provided by Mr. Randy Raban, Manager of the Hydraulic Operations Department of Manitoba Hydro, has been very much appreciated.

A major contribution was made by the Canadian Coast Guard, facilitated by Mr. Tom Anderson, Captain Vic Isidoro and Captain Manu Unni-Nayar, Coast Guard Central Region Headquarters, Sarnia, Ontario. Guidance, leadership and the unfailing assistance provided by Captain Rob Aitchison, First Officer John Hanson, and the crew of the CCGS *Namao* greatly aided field activity. Ray Settee, Lynn Clemons and the staff of the Canadian Coast Guard Base in Selkirk are also acknowledged for their role in supporting logistics on both Lake Winnipeg and Lake Manitoba.

Ron Good, Mike Gorveatt and Tony Atkinson are acknowledged for their role in preparing survey equipment. Larry Johnston and Darrell Beaver prepared the navigation equipment. Andy Sherin provided software and guidance for daily plotting of navigation data.

Ron DiLabio oversaw the process of critical review. The following reviewers contributed to the improvement of this report: René Barendregt, Ron DiLabio, Larry Dyke, Rod Klassen, Matthew Leybourne, Roger McNeely, Peta Mudie, Mark Nixon, Susan Pullan, John Shaw, Bob Taylor, and Jean Veillette.

4. Cruise report - *Namao* 96-900

4. Cruise report of the 1996 Lake Winnipeg Project: *Namao* 96-900

B.J. Todd[1]

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4.1 NARRATIVE ACCOUNT OF THE CRUISE - *B.J. Todd and D.L. Forbes*

The CCGS *Namao* was visited at her berth at Canadian Coast Guard Base Selkirk by Todd and Nielsen on May 27, 1996. Discussions that day with Coast Guard personnel dealt with outfitting and operation of the ship during August and September.

Throughout July, 1996, M. Gorveatt of the GSC Atlantic (GSCA) supervised assembly of geophysical and geological equipment at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia. Two containers were used: a 6 m-long container was packed with the equipment while a 2 m by 2 m refrigerated container was prepared for shipping cores from Manitoba to Nova Scotia at the conclusion of the cruise. From **August 4-5 (Days 217-218),** the two containers were transported by tractor trailer to Ottawa. R.L. Good, R.A. Burns and M. Douma, all of TSD, assembled geophysical equipment in Ottawa. This equipment was added to the shipment and the full complement of gear was transported from Ottawa to the Coast Guard Base at Selkirk, Manitoba from **August 5-6 (Days 218-219).** Scientific and technical staff arrived in Selkirk from **August 5-7 (Days 218-220)** and stayed in commercial accommodations in Selkirk while the ship was outfitted.

The materials that had been used to construct the scientific lab in the hold of the CCGS *Namao* in 1994 had been stored for two years at the Manitoba Energy and Mines warehouse in Winnipeg. These materials were delivered to Selkirk Coast Guard Base two weeks prior to the arrival of scientific staff. After telephone consultation with Todd in mid-July, Coast Guard personnel erected the laboratory along the starboard side of the forward hold (Fig. 1). This arrangement was a considerable improvement relative to 1994 with respect to mobilization of laboratory electronics.

In mid-July, M. Gorveatt of GSCA and Coast Guard staff (Table 1) arranged the delivery of a 6 m by 2.4 m accommodation trailer to the Coast Guard Base. By the time scientific staff arrived, this trailer had been outfitted with bunks for four staff as well as an area of office space. This trailer was secured for the duration of the cruise on the starboard side of the upper deck (Fig. 1). Space was made available in a ship's cabin for two members of the scientific staff. At times during the cruise, members of the scientific staff slept in the hold or in tents onshore.

Scientific staff (Table 2) spent **August 7-8 (Days 220-221)** working with Coast Guard personnel loading geophysical survey equipment onto the CCGS *Namao* from the dock. Navigational gear was mounted on the bridge and above the bridge on the bridge deck (Fig. 1). All data recording and logging electronic components were secured in the scientific laboratory and all gear to be towed behind the ship was secured on the deck at appropriate locations (Fig. 1). Geophysical and navigational equipment were secured in the CCGS *Namao's* yawl and these instruments were tested in the Red River. Coring equipment was placed in storage in the shipping container on the dock until completion of the geophysical survey phase of the cruise.

On **August 9 (Day 222)**, the CCGS *Namao* departed the Coast Guard Base dock at 0900 and steamed north through Netley Marsh. The mouth of the Red River, at the south end of the South Basin of Lake Winnipeg, was reached at 1100. From here, the ship steamed slowly northward to the fairway buoy (marking the shipping channel into the basin) while the multi-channel seismic system, the high-resolution single-channel seismic IKB-Seistec system (hereafter, the Seistec system), and the sidescan sonar (see section 4.3) were deployed. **Line SB12** was run from the fairway buoy to the northeast (Fig. 2). (Note that Appendix 10.1 provides plots of CCGS *Namao* and yawl survey lines and sample sites). The objectives of this line were to test survey and navigation equipment and test for a transition from Paleozoic bedrock to the west to Precambrian bedrock to the east (Fig. 2). The beginning of line SB12 ties with the south end of line SB3 (from *Namao* 94-900) and the end of line SB12 ties with the east end of line SB2 (also from *Namao* 94-900).

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[1] **With contributions from D.L. Forbes, C.F.M. Lewis, L.H. Thorleifson, R.A. Burns, C.B. Chapman, M. Douma and P.R. Girouard (Geological Survey of Canada) and E. Nielsen (Manitoba Energy and Mines). Careful reviews by L. H. Thorleifson and John Shaw improved the accuracy of the cruise report.**

The sidescan sonar record from line SB12 showed extensive furrowing of the lakefloor along this line. The presence of gas in the sediments rendered them opaque to the Seistec system so the high-resolution seismic record contains little subsurface information. A paper record output of the multi-channel seismic system was not available on this line as the EPC recorder was in transit from New Brunswick to Winnipeg. However, the multi-channel data were digitally recorded (see section 4.3.1) and processing of these data will reveal if the Paleozoic/Precambrian contact was imaged. A logger recorded CO_2 concentration in surface waters and water samples were collected while the ship was operating at survey speed. At 1430 the geophysical gear was retrieved and the ship steamed for Gimli harbour where the CCGS *Namao* was secured at 1550.

Over the weekend of **August 10 and 11 (Days 223 and 224)**, the CCGS *Namao* was secured in Gimli harbour. On **August 10 (Day 223)**, F. Gnitzinger acted as coxswain in the yawl with Forbes and Douma as crew. After a few hours of preparation, the yawl was away at 1100 and back aboard at 1530, having surveyed **lines 100-111** on the Gimli Beach shoreface and at a site known as "The Mounds" (survey site 31 of Penner & Swedlo, 1974; see Fig. 18 of Forbes & Frobel, 1986). Nielsen and Thorleifson placed survey markers on the cliff at this site so that the yawl could reoccupy the profile surveyed by Penner and Swedlo in the early 1970s. DGPS navigation was obtained using the Trimble system with a base station on the stationary CCGS *Namao*. Todd and Lewis spent the day planning details of the cruise and tabulating latitudes and longitudes of survey line way points. Nielsen and Thorleifson joined the planning session in the late morning and then departed for Winnipeg. At the same time as cruise planning was underway, alterations and improvements were made to the geophysical equipment both on the deck and in the laboratory and to the navigation setup on the bridge. Most notably, the batteries in the uninterruptable power supply (UPS) in the geophysics laboratory were diagnosed as faulty and were replaced. On **August 11 (Day 224)**, F. Gnitzinger again acted as yawl coxswain with Forbes and Douma as crew. Chapman accompanied the yawl for the first three hours to set up the sidescan sonar system. The yawl was away from 0910 until 1155, surveying **lines 111-118** on the shoreface off the north side of Willow Point. During the afternoon, the yawl departed at 1325 and samples were collected off Gimli and 'The Mounds'. The Ekman grab was used to obtain **samples 301-304** in 2.4 to 6.1 m water depths off Gimli and **samples 305-308**, consisting of stiff clay and burrowed mud clasts with pebbles, in depths of 1.7 to 3.3 m off 'The Mounds'. The yawl returned to the ship at 1625. High-quality DGPS navigation was again provided by the Trimble system with the base station onboard the CCGS *Namao*. The picking of way point locations and navigation computer updating continued throughout the day. Nielsen brought a shipment of geophysical equipment from Winnipeg at 1600 and then returned to the city.

On **August 12 (Day 225)**, the CCGS *Namao* departed from Gimli harbour at 0845 and steamed northeast for Elk Island. Coast Guard crew worked in cooperation with scientific staff to construct a waterproof covering for the geophysical instruments in the yawl. This was completed and the ship was stopped to put off the yawl at 1025 with Forbes, Douma, Nielsen and Coxswain Sparkes aboard. The yawl worked off the southwest side of Elk Island and surveyed **lines 119-131**, including sidescan coverage of an extensive area of ice scour features on the lakebed in deeper water (lines 129-130). Navigation was provided by the Magnavox GPS and AGCNAV system with corrections transmitted from CCGS *Namao*. With light winds, the yawl returned independently across the lake on mirror-smooth water, arriving in Gimli Harbour about 1600. Meanwhile, the CCGS *Namao* re-occupied a portion of line SB4 from *Namao* 94-900 and surveyed along this line, with the new designation **line SB13**, southeast into Traverse Bay (Fig. 2). The ship then altered course and reversed the survey direction along the same portion of line SB4, but offset 150 m to the north. The purpose of line SB13 was to resurvey a portion of line SB4 which had revealed extensive lakefloor furrowing. Furrows developed over the intervening two years will be identified by comparing the two different records. The 150 m-offset portion of line SB13 was designed to overlap with the previous portion of the line to map a 350 m-wide swath of lakefloor with the sidescan sonar. CO_2 logging and water sampling were coordinated by Thorleifson. The geophysical gear was brought on board at 1415 and the ship steamed back to Gimli harbour, arriving at 1613.

Rain and strong east winds prevailed on **August 13 (Day 226)**. The CCGS *Namao* departed Gimli harbour at 0830 and steamed north to a position south of Hecla Island. The yawl was not deployed due to the wind and waves. At

1030, the geophysical gear was deployed and Chapman discovered a short in the power plug of the ORE power supply for the Seistec system. The plug was removed and the power cord was "hard wired" into the power supply. **Line SB14** was run due east to intersect line SB5 from *Namao* 94-900 at the position of Pearson Reef (Fig. 2) primarily to obtain seismic images of bedrock geology. The signal from the "line-in-cone" array on the Seistec catamaran was degraded by the action of the waves so the signal to the EPC recorder was changed to the Seistec external eel for a slightly improved signal. The single-channel feed from the multi-channel eel provided the best image (highest signal to noise ratio) of the Pearson Reef Moraine and the sediment-filled basins flanking it to the west and the east. CO_2 logging and water sampling were coordinated by Thorleifson. At 1445, the geophysical gear was retrieved and the ship steamed north through the passage between Black Island and Hecla Island and was secured at Gull Harbour dock at 1640. Thorleifson and Douma departed for Winnipeg.

August 14 (Day 227) was sunny with light winds. The CCGS *Namao* departed Gull Harbour at 0830 and steamed south to intersect line SB5 from *Namao* 94-900 south of Black Island. The ship was stopped for a short time at 0905 for the yawl to be put over with Forbes, Nielsen and Coxswain Sparkes aboard. The yawl proceeded to Observation Point in the northeast corner of South Basin, where it surveyed geophysical **lines 132-138**. Navigation for these lines was provided by the Magnavox and AGCNAV system, but DGPS corrections were not received from CCGS *Namao*. The yawl party put ashore to survey the beach and sample beach sediments. A number of rooted tree stumps below present lake level were also collected. The yawl put out from Observation Point by 1500 and proceeded north through the mid-lake passages toward Pine Dock. Meanwhile, at 0920 the CCGS *Namao* deployed the geophysical gear and steamed along **line SB15** north through the channel between Hecla Island and Black Island and continued north through the passage between Deer Island and Grindstone Point (Fig. 2). The north end of line SB15 intersected line SB6 from *Namao* 94-900 in Washow Bay. Line SB15 was designed to investigate channel areas for bedrock geology and evidence of the southward migration of Lake Winnipeg. The geophysical gear was retrieved at 1450 and the ship steamed north to Pine Dock. After repeated failed attempts to contact the yawl via radio, the CCGS *Namao* altered course and steamed south to search for the yawl. By 1628, radio contact was established and the yawl was on board by 1650. Once again, the CCGS *Namao* steamed north and was secured at Pine Dock at 1720.

August 15 (Day 228) was sunny with almost no wind. The yawl departed from Pine Dock at 0818 with Forbes, Nielsen and Coxswain Sparkes on board and headed north for Berens Island. The yawl completed geophysical survey **lines 139-156** on the shoreface off the north shore beach and barrier complex on Berens Island. The sidescan struck the lakefloor and was damaged. Again the DGPS corrections could not be received from the CCGS *Namao*, resulting in poor-quality positioning for these lines. Some time was also devoted to inspection of the shingle barrier and associated washover deposits at the northwest corner of the island. The CCGS *Namao* departed Pine Dock at 0830 and steamed north through The Narrows. At 0955, the geophysical gear was deployed on line **NB16** (Fig. 2). The first nautical mile of this line overlaps a portion of line NB7 from *Namao* 94-900. Line NB16 serves to partially fill the 1994 gap in geophysical line coverage extending from The Narrows to George Island. The ship proceeded north along the line toward Berens Island. Burns recognized a problem with the multi-channel seismic system which was not initiating recording at a consistent time delay after the firing of each sleeve gun shot. Chapman solved the delay inconsistency by removing the system connection to the EPC recorder and by grounding the system to an instrument rack. By 1500, watch keepers in the geophysical laboratory noted that the Seistec record was degrading by becoming dominated by low frequency signals, a symptom similar to that noted in previous years on other projects. At 1706, the geophysical gear was recovered, the yawl was brought on board southeast of Berens Island. The CCGS *Namao* steamed to Berens River where the ship was secured at 1815.

After much discussion with GSCA personnel in Dartmouth and Resolute regarding the nature and possible solution of the Seistec problem, it was concluded that a Huntec boomer would be sent from GSCA to replace the boomer on the Seistec.

The weather on **August 16 (Day 229)** was sunny but with 30 knot winds from the northwest. The ship departed from Berens River at 0830 and steamed into the lake. Wave conditions precluded yawl operations and the ship proceeded to a position northwest of Berens Island. The multi-channel seismic system and sidescan sonar were deployed at 1113 and line **NB17** was surveyed to the east in an attempt to intersect the Paleozoic/Precambrian contact (Fig. 2). The geophysical equipment was recovered at 1242 and the CCGS *Namao* steamed back to the Berens River dock where the ship was secured at 1430. Most of the ship's officers and crew travelled home for the weekend from the Berens River airport, departing at 1645. Chapman isolated the problem with the Seistec system to a leak in the boomer and began to fix the problem.

The weekend of **August 17-18 (Days 230-231)** was spent secured to the dock at Berens River during two days of excellent weather. On **August 17 (Day 230)**, Forbes, Nielsen and Coxswain Magnusson departed in the yawl at 0900 and worked onshore at Disbrowe Point, the large spit enclosing Paterson Bay at the mouth of Berens River. Activities included beach surveys and sampling. The yawl party also collected samples of wood for dendrochronological and radiocarbon analyses. The yawl returned to the ship at 1715. Chapman and Asprey rebuilt the Seistec boomer and sealed the leak. The system was deployed behind the ship next to the dock and tested for two hours. On **August 18 (Day 231)**, Forbes, Nielsen and Coxswain Magnusson departed in the yawl at 0900 and returned to the north shore of Berens Island. The work included geophysical **lines 157-158** and collection of grab **sample 309**, consisting of angular mud clasts, in 4.8 m of water. High-resolution DGPS positioning was obtained using the Geotracer 2000 RTK system with a base station on the beach at GSC benchmark 310, which was installed for this purpose. Beach surveys and sampling were completed at the benchmark site before returning to the ship at Berens River at 1515. During the day on board ship, portions of this cruise report were prepared and a suite of potential coring sites was selected. The boomer did not arrive at the Berens River airport so arrangements were made to have it picked up in Winnipeg and delivered to the Coast Guard crew for arrival the next day.

The weather in the morning of **August 19 (Day 232)** was very bad. High winds from the north and large waves made surveying impossible and made sailing uncomfortable. The crew arrived by air at 0800 and the ship departed from Berens River at 0830. Once out on the lake, the decision was made not to deploy the geophysical gear and the ship steamed north to George Island, arriving at the dock at 1313. The weather improved during the afternoon, and Forbes, Nielsen and Coxswain Sparkes departed in the yawl at 1500 to survey the south shore of George Island. The yawl completed **lines 159-163** extending from the beach to the outer shoreface and covering part of an extensive boulder patch off the southern extremity of the island. Navigation utilized the Geotracer 2000 RTK system with the base station installed at GSC benchmark 322, about 20 m south of the fish plant near the George Island wharf. The sidescan fish was damaged by impact against an isolated large boulder projecting to within 2 m of the lake surface. The yawl returned to the dock at 1620.

The winds were light during the morning of **August 20 (Day 233)** and the yawl put out at 0915 with Forbes, Nielsen and Coxswain Sparkes on board for work around George Island. Grab **samples 310-313**, ranging from medium sand to silty clay, were collected in water depths of 2.8 to 13 m off the southeast coast of the island in the area surveyed the previous day. Survey **lines 164-167** were completed off the south and southwest coast of the island. Landings were made near the southernmost point to investigate remains of a wreck and at the west end of the island to examine the high dune and beach there. Following this shore survey, the yawl continued around to the north side of the island, where survey **lines 168-169** were run out from beaches at the northeast end (opposite the harbour) and grab **sample 314** produced yellow fine sand in 2.8 m of water. DGPS positioning for the sampling program and for lines 164-166 and 168-169 used the RTK system with the same base station as the previous day. Loss of the base station signal at the west end of the island reduced the navigation for line 167 to dead-reckoning. Following a rough passage around the east end of the island, the yawl returned to the wharf at 1600. Meanwhile the CCGS *Namao* departed George Island dock at 0839. The geophysical gear was deployed at 0849 just as the ship cleared the harbour entrance buoys to begin **line NB18** toward the south (Fig. 2). An excellent image of the south shoulder of the George Island Moraine was obtained at the start of the line with the rejuvenated Seistec system. Line NB18 serves to fill the remaining gap in 1994 geophysical line coverage. The ship steamed south along the line and imaged a 15-m high north-facing scarp at the south end of the line. The wind speed increased slightly in the afternoon and the geophysical gear was retrieved at 1420. By the time the ship arrived back at George Island at 1618, the wind speed had increased appreciably from the south.

On **August 21 (Day 234)**, the winds were westerly from 15-20 knots with some swell resulting. The ship departed George Island dock at 0650 and steamed around to the north of the George Island Moraine. The geophysical gear was deployed at 0750 about three nautical miles south of the position of core 107 from *Namao* 94-900. The CCGS *Namao* steamed northwest along **line NB19** (Fig. 2) through the position of core 107 and beyond until 1300 when the geophysical gear was retrieved. During the day's survey, the signal-to-noise ratio was reduced due to the weather but the data quality was acceptable. During transit to Grand Rapids, the electronics in the geophysics laboratory were dismantled and boxed to be ready for unloading. The ship was secured at

Grand Rapids at 1715 and the sewage tanks were (fortunately) pumped out. Jodrey arrived in Grand Rapids having travelled from Halifax.

August 22 (Day 235) dawned sunny and warm which was fortunate for the morning's dockside operations. At 0800, the crew and scientific staff emptied the geophysics laboratory of all equipment. The equipment was then mustered on the dock for sorting into appropriate shipping boxes and labelling. The container with all the coring equipment arrived by flatbed truck from Selkirk at 0800 and this material was stowed in the appropriate locations on the ship. The container was then packed with the geophysical equipment and was returned to the Selkirk Coast Guard Base dock for storage. The transition from geophysical survey equipment to coring operations equipment was completed by 1200. At 1105, the yawl departed with Forbes, Nielsen and Coxswain Sparkes for survey work offshore from Grand Rapids. Survey **lines 170-182** were completed off the mouth of the Saskatchewan River, including a long tie line with the west end of line NB9 from Namao 94-900, and reconnaissance lines along the gravel and peat shoreline north of Grand Rapids. Positioning was non-differential GPS. Grab **samples 316-317** were obtained on a broad bank of pebbly silty sand and silt lakeward of the river mouth in depths of 9.7 to 11 m, the second sample being taken with the anchor. Meanwhile, Burns and Girouard left the CCGS *Namao* to travel to Winnipeg and fly home.

The CCGS *Namao* left the Grand Rapids dock at 1230 and proceeded to **core site 201** (on line NB9, *Namao* 94-900, Fig. 3) off the mouth of the Saskatchewan River where the ship was anchored at 1317 and manoeuvred into the coring position. The first attempt at a gravity core penetrated too far into the soft lakefloor sediments. Two of the four lead collar weights were removed and the second attempt to recover a 2 m gravity core was successful at 1436. The 9 m piston core required rigging alterations but ultimately was successfully deployed at 1609. At 1623, the anchors were weighed and the ship steamed to the Grand Rapids dock, arriving at 1718. The yawl and crew were waiting on the dock, having arrived some time earlier. The yawl sidescan sonar was once again inoperative. Processing of the cores continued until 2000. Thorleifson rejoined the cruise and was briefed on activities.

August 23 (Day 236) was sunny but with a stiff breeze from the south. The CCGS *Namao* departed Grand Rapids dock at 0830 and steamed northeast to **core site 202** southeast of Limestone Bay at the north end of line NB11 (*Namao* 94-900, Fig. 3). The yawl was put off at 1135 with Forbes, Chapman and Coxswain Sparkes on board. After an uneventful passage to the mouth of Limestone Bay, hopes of obtaining profiles over submerged ridges behind Limestone Point (Forbes and Frobel, 1996) were dashed by shallow water that prevented the yawl from entering the bay. As an alternative, the yawl proceeded east along the 20 km outer shore of Limestone Point, running sidescan and bathymetric surveys on **lines 183-190**, including shore-normal profiles across the shoreface to the near shore bar off the beach. Positioning was by non-differential GPS. By the end of line 190 at 1615, the wind had increased from the south and there followed a difficult 40 km passage along the north shore of the lake to Two Mile Channel, with short-period waves, 1.5 m or higher, on the starboard beam. Meanwhile, the CCGS *Namao* anchored at **core site 202** at 1238 and deployed a 2 m gravity corer, outfitted with a new wooden collar to limit penetration, at 1250. A deployment of the 9 m piston corer followed at 1332 and the ship weighed anchor at 1352 and steamed to Warren Landing, tying up at 1705. Thorleifson completed four zooplankton net hauls and water sampling throughout the day. Core processing on the dock continued until about 1930. The yawl arrived at Warren Landing at 1950 after transiting Two Mile Channel and Playgreen Lake.

On **August 24 (Day 237)**, the winds increased in speed during the day and swung from west to north. The CCGS *Namao* departed Warren Landing at 0830 and steamed southwest out the passage while the yawl went ahead with a Coast Guard crew and corrected the positions of some buoys. The yawl worked in Playgreen Lake for the day, departing from the ship at 0915 with Forbes, Lewis and Coxswain Sparkes on board. A GPS base station was established at Canadian Hydrographic Service benchmark 8402 on Kettle Island and geophysical **lines 191-194** were run along and across the channel northwest of the island in Playgreen Lake. Navigation by a combination of non-differential and Geotracer RTK differential GPS provided a good measure of the errors associated with the non-differential system. Grab **samples 318-319** of fine sand and sandy mud were collected in depths of 2.7 and 5.2 m, marking the first use of the mini van Veen sampler on this cruise. The samples suggest that prominent lakebed channels are active, possibly flushed by Lake Winnipeg outflow under the ice during winter. Some time was spent examining furrows and elliptical scours in bedrock, suggestive of subglacial meltwater scour on Kettle Island. The ship, meanwhile, proceeded southwest to **core site 203** (replicating core 103) along NB9 (*Namao* 94-900, Fig. 3). After anchoring at 1107, the ship was positioned and a 2 m gravity core was obtained at 1113. A piston core was recovered at 1142 and the ship weighed anchor at 1155. **Core site 204** to the northeast (line NB9, *Namao* 94-900, Fig. 3) was reached at 1309 and a gravity core recovered at 1314. A piston core was retrieved at 1337 and the ship weighed anchor at 1345 to return to Warren Landing. By this time, the wind had increased in speed producing significant waves from the west. Thorleifson conducted water sampling and zooplanton net hauls throughout the day. The ship was secured at Warren Landing at 1524 and the yawl returned to the dock about 1630. The Seistec system electronics were mounted in the accommodation trailer to provide seismic information at future core sites. Core processing proceeded on the dock until about 1900 and a strategy meeting was then held to plan a coring timetable for the remainder of the cruise.

Winds were light on **August 25 (Day 238)** and the CCGS *Namao* departed Warren Landing at 0830 and steamed southwest out the passage. The yawl departed the ship at 0927 with Forbes, Nielsen and Coxswain Sparkes to work in the vicinity of Spider Islands on the northeast shore of the North Basin. At 1129, the yawl started survey **line 195** about 3.5 km southwest of Spider Islands point, running onshore to the barrier beach about 500 m north of the inlet. Positioning was by non-differential GPS. Much of the day was then spent ashore, surveying the beach and dunes and collecting samples of drowned stumps on the north side of the point. Grab **sample 320**, of gritty mud, was obtained at 1610 on an erosional profile in Lake Agassiz deposits at a water depth of 11 m. Aboard the CCGS *Namao*, from 0950 to 1030, Seistec survey line **NB20** was conducted along a portion of line NB9 (*Namao* 94-900) to check core sites (Figs. 2, 3). Even though the Seistec record was of very high quality, the record did not correspond to line NB9 probably due to slight errors in position combined with high local bedrock relief. Therefore, two core site positions were selected from the new line. The ship anchored at 1150 but the DGPS demonstrated significant drift (up to 100 m) during ship positioning at **core site 205** (Fig. 3). Finally, coring operations retrieved a gravity core at 1239 and a piston core at 1319. The ship weighed anchor at 1333 and moved about half a kilometre to the southwest and anchored at 1344 at **core site 206** (Fig. 3). Again, positioning the ship using the DGPS was frustrating. Fortunately, the Seistec was deployed off the port quarter and that record was consulted to ensure that the ship was positioned over the desired geological target. At 1408 a gravity core was recovered, followed by a piston core at 1437. Thorleifson collected the final zooplankton net haul. The ship weighed anchor at 1456 and steamed south for George Island. Water sampling was conducted throughout the day. Core processing proceeded on the foredeck during the transit south. The yawl was brought on board at 1700 and the ship was secured at the George Island dock at 1940.

There was no wind at the beginning of **August 26 (Day 239)** and the CCGS *Namao* departed George Island at 0800. The yawl left the ship at 0820 with Forbes, Nielsen and Coxswain Magnusson and returned briefly to the west end of George Island to obtain a non-differential GPS fix at the beach, 27 m seaward of GSC benchmark 324. A short Knudsen sounder profile, **line 196**, was run with non-differential positioning, out from the beach south of Marchand Point and samples of wood and sand were obtained onshore. With the wind picking up from the southwest, the coxswain was anxious to get away and the yawl returned to the ship, south of George Island, to find the lake surface almost flat. The ship reached **core site 207** (line NB8, *Namao* 94-900) in the Cannibal Basin southwest of George Island and anchored at 0910 (Fig. 3). The coring crew recovered a gravity core at 0925 and a piston core at 0955. The ship weighed anchor at 1014 and steamed to **core site 208** along line NB18 (*Namao* 96-900) in Berens Basin south of George Island (Fig. 3). The CCGS *Namao* anchored at 1130 and the yawl was brought alongside at 1138. A gravity core was recovered at 1240 and a piston core was recovered at 1302. By this time, the wind was beginning to increase in speed, so the yawl was placed on the foredeck and the anchor was weighed at 1330. The ship steamed south to **core site 209**, also situated on line NB18, anchoring at 1427 (Fig. 3). A gravity core was retrieved at 1449 and a piston core at 1511. The anchor was weighed at 1530. By this time, the waves had increased to such a height to render core processing on the foredeck impossible. The CCGS *Namao* steamed southeast to the east end of line NB17. The ship did not anchor here but obtained a van Veen grab of mud at **site 210** at 1628 and a van Veen grab of gravel at **site 211** at 1637 (Fig. 3). Water sampling was conducted throughout the day. The ship then travelled to Berens River, arriving at the dock at 1825. Core processing continued on the foredeck until 2000.

The winds on **August 27 (Day 240)** were initially strong from the south but wind speed (and wave height) decreased throughout the day and shifted to westerly. The CCGS *Namao* departed the Berens River dock at 0800 and steamed south into the Black Bear Basin to **core site 212** along line NB16 (*Namao* 96-900, Fig. 3). The ship did not anchor at this site due to high waves. Two attempts to obtain a gravity core failed; in the first attempt the corer tipped over and in the second attempt, the corer emptied its contents onto the deck. A core was retrieved successfully at 1111. The ship steamed to the south end of line NB16, bypassing a desired core site due to high wave conditions, and anchored at **core site 213** at 1220 (Fig. 3). By this time, the wind had decreased and allowed both gravity and piston coring to proceed. A gravity core was recovered at 1246 and a piston core was recovered at 1323. The CCGS *Namao* weighed anchor at 1335 and then steamed north to reoccupy the previously bypassed **core site 214** (Fig. 3). The ship anchored at 1408 and recovered a gravity core at 1421 and a piston core at 1438. The ship weighed anchor at 1455 and proceeded to End of the Road where the ship was secured at 1615. Thorleifson conducted the final day of water sampling. Core processing continued until approximately 2000. A Manitoba Energy and Mines summer student met the ship to drive Forbes and Chapman to Winnipeg. Chapman was leaving the ship and Forbes was to return via Selkirk, to locate additional paper for the yawl sidescan in the GSC container at the Coast Guard Base. The government vehicle broke down outside Gimli and the party eventually hired a taxi to complete the trip to Winnipeg. Forbes rented a car to complete his objective, returning to the ship around 0200 on August 28.

The weather on **August 28 (Day 241)** was sunny and calm. Thorleifson departed from the ship at 0800 to scout the eastern shore of Lake Manitoba for the upcoming trial survey and to deliver water and biological samples to the Freshwater Institute in Winnipeg. The yawl departed at 0832 with Forbes, Nielsen and Coxswain Sparkes on board. The ship then departed End of the Road and steamed south through Washow Bay to **core site 215** at the north end of line SB15 (*Namao* 96-900, Fig. 3). The ship anchored at 1103 and a gravity core was recovered at 1117 and a piston core was recovered at 1138. After weighing anchor at 1155, the ship proceeded south to **core site 216** west of Deer Island, again along line SB15 (Fig. 3). The ship anchored at 1225 and recovered a piston core at 1240. During piston core deployment over the side of the ship, the cable clamp slipped because it was worn and the entire assembly had to be brought back on board ship and the clamp was replaced. Finally, a piston core was successfully recovered at 1345. After weighing anchor at 1357, the ship steamed south through the passage between Hecla Island and Black Island to **core site 217** on line SB15 south of Black Island (Fig. 3). The ship anchored at 1455 and recovered a gravity core at 1500 and a piston core at 1520. After weighing anchor at 1530, the CCGS *Namao* steamed north through the passage and was secured at the Gull Harbour dock at 1606. Core processing on the foredeck and the dock continued until approximately 2000. Meanwhile the yawl put ashore on a small gravel foreland at the southeast corner of Black Bear Island, immediately south of the light, at 0900. After completing shore surveys at this site, the yawl proceeded to the area of large sand waves immediately north of The Narrows, where it ran geophysical **lines 197-204**, the last of these extending into and across The Narrows, finishing about 100 m off the eastern shore south of East Doghead Point. Positioning was by non-differential GPS. Grab **samples 321-322** were attempted over the largest sand wave north of The Narrows. Nothing was obtained in the first of these, after three attempts in 25 m of water, but a small amount of Lake Agassiz mud came up on the arms of the van Veen sampler. Five attempts were made for the second sample, eventually yielding a few clasts of pea gravel from a water depth of 21 m. The yawl arrived at Gull Harbour around 1600.

On **August 29 (Day 242)** the weather was once again sunny and calm. The yawl departed before 0830 with Nielsen and Coxswain Magnusson on board to spend the day collecting wood samples at Observation Point on the eastern shore of the South Basin. The CCGS *Namao* departed Gull Harbour at 0830 and steamed south into the South Basin. For line **SB21**, the Seistec was deployed on line SB5 (*Namao* 94-900) and the ship steamed southwest to repeat a small portion of the line across the original discovery section of Pearson Reef Moraine. Then the ship turned and steamed a short repeat portion of line SB14 (*Namao* 96-900, Fig. 2) followed by a series of three west-east profiles across the moraine. The Seistec survey was completed at 1155 and the following hour was spent selecting three core sites in a mud-buried paleo-beach system on the moraine. At 1257, the ship anchored at **core site 218** (Fig. 3) over the beach crest on the east side of the moraine. A piston core was recovered at 1314. The anchor was then dragged to **core site 219** (Fig. 3) over the back-barrier lagoon. A gravity core was recovered at 1346 and a piston core was recovered at 1415. At 1420, the anchor was dragged back over the beach to **core site 220** (Fig. 3) over the lower clinoform interval which possibly represents a paleo-shoreface. A gravity core was recovered at 1504 and a piston core was recovered at 1524. The anchor was weighed at 1534 and the ship returned to Gull Harbour at 1704. The yawl had returned to Gull Harbour a couple of hours earlier. Core processing continued until about 2000. Thorleifson arrived and transported Asprey and some geophysical equipment to Winnipeg.

August 30 (Day 243) was sunny, warm and humid with a stiff southerly wind that decreased in speed during the day. The yawl left the Gull Harbour dock before 0830 with Forbes, Nielsen and Coxswain Magnusson on board and headed into the South Basin. The CCGS *Namao* departed Gull Harbour dock at 0830 and steamed into the South Basin.

Due to the high wind and waves, the yawl was recovered on board at 0858. The ship steamed to **core site 221** (line SB14, *Namao* 96-900, Fig. 3) and anchored at 1017. A gravity core was recovered at 1038 but wave conditions were too severe to attempt a piston core. The ship weighed anchor at 1052 and steamed west to **core site 222** (line SB14, *Namao* 96-900, Fig. 3) where a gravity core was collected at 1124 but once again no piston core was attempted. The ship then steamed south to **core site 223**, a replicate of core 122 (line SB3, *Namao* 94-900, Fig. 3). The ship anchored at 1300 and by this time, the wind and waves had moderated. In order to keep the foredeck clear for coring, the yawl was put off with Coxswain Magnusson on board. A gravity core was recovered at 1312 and a piston core was recovered at 1331. Forbes then joined Coxswain Magnusson in the yawl to conduct a sidescan survey in an attempt to locate the core head of the corer lost at this site in 1994. A number of indistinct targets were observed and plans to attempt a recovery of this corer were abandoned. The CCGS *Namao* weighed anchor at 1430 and steamed for Gimli Harbour where the ship was secured at 1512. The ship's crew and Nielsen departed about 1600 and the core was processed until about 1830. In preparation for work on Lake Manitoba, the Seistec gear was dismantled and loaded, along with the sidescan sonar equipment, onto a Coast Guard truck. Todd, Lewis and Thorleifson travelled to the Selkirk Coast Guard Base and then in tandem with Clemons, towing the Coast Guard Boston Whaler, to Portage la Prairie, arriving at 2300.

On Lake Winnipeg on **August 31 (Day 244)**, the yawl worked in the southwest corner of the South Basin from 0830 to 1615 with Forbes, Jodrey, and Coxswain Hansen on board. Before setting out, they discovered that both of CCGS *Namao*'s bow lines had been slipped and stopped to make them secure. They were then delayed providing assistance to a fishing boat with motor trouble, eventually towing it back into Gimli. The passage south to Matlock was slow, dodging nets and beating into a head wind. A landing was made on the beach at Sans Souci to survey the shore and collect beach sediment samples. The yawl then ran a rectangular pattern on **survey lines 205-211**, extending east to Chalet Beach and north to the area off Matlock. Precise navigation was obtained with the Geotracer 2000 RTK system, using a base station on the beach at Sans Souci. Grab **sample 323** brought up angular mud clasts of Lake Agassiz sediment from a water depth of 2.2 m. In Portage la Prairie, Teller (University of Manitoba) arrived at 0900 and the crew drove north to Lynch's Point on the southwest shore of Lake Manitoba. The Boston Whaler was put in at the dock and from 1000 to 1400, Seistec and navigation equipment was loaded onto the boat. The ORE power supply failed when the system was started and the rest of the afternoon was spent troubleshooting. Todd, Lewis, Thorleifson and Teller drove to the Selkirk Coast Guard Base and retrieved ORE spares at 2100 and returned to Portage la Prairie at 2330.

On Lake Winnipeg on **September 1 (Day 245)**, yawl work was precluded by high wind and waves. Instead, the core section ends were waxed in the core storage in the hold. At Lynch's Point on Lake Manitoba, the control board and fuse of the ORE power supply were replaced and the system worked. The boat left the dock at 1330 and surveyed out the channel and into the lake. Except for a short time at the mouth of the dredged channel, the record was obliterated by gas in the sediments. The survey line headed to site D3 until 1500 when the waves became too high to survey safely. The Seistec was brought on board and the boat returned to the channel about 1600 and was secured in the anchorage.

On Lake Winnipeg on **September 2 (Day 245)**, the yawl departed Gimli at 0830 with Forbes, Jodrey, and Coxswain Hansen on board. Surveys and shore sampling were conducted along the west side of the lake at Balaton Beach, north of Hnausa, including samples for the United States Geological Survey (USGS) Red River basin study. A GSC benchmark was installed at Balaton and shore surveys completed, after which the yawl ran survey **lines 212-217** over the near shore and shoreface. Precise positioning was obtained using the RTK system with a base station at the new benchmark onshore. Grab **sample 324** produced silty mud with pebble-cobble gravel in 3.3 m of water. The yawl returned to Gimli at about 1545. On Lake Manitoba, the boat left the dock at 0800 and travelled northeast to site D1. Wind and waves were moderate from the south. The Seistec was deployed at 0900 and a line was surveyed south through sites D2 and D3 and then west across the submerged paleo-Assiniboine River. Once again, the Seistec survey was unsuccessful, apparently due to gas, except for a 5 minute-long window in the fluvial deposits. The wind came up very quickly from the west and the Seistec gear was brought on board about 1430. Passage west to the anchorage was slowed, first due to wind and waves, and subsequently as the propellers became fouled in an anchor line. The boat was secured at the dock at 1600. The geophysical and navigation equipment was unloaded and the boat was pulled on to its trailer by about 1700. Teller left for Winnipeg. Clemons drove the boat to the Selkirk Coast Guard Base in Selkirk. Todd, Lewis and Thorleifson drove to Portage la Prairie to dismantle the GPS base station on top of the Canadian Tire store and then drove on to Selkirk, arriving at the Coast Guard

Base at about 2100. Geophysical equipment to be returned to the CCGS *Namao* was loaded on to the Coast Guard truck and the remainder was placed in the shipping container. Todd, Thorleifson and Lewis then travelled to the ship at the Gimli pier, arriving and unloading the geophysical gear at 2300. Thorleifson then returned to Selkirk with the truck.

September 3 (Day 247) was sunny with stiff winds from the southwest. The ship's crew arrived from Selkirk shortly after 0800 and the CCGS *Namao* departed Gimli pier at 0833. The yawl left the ship at 0846 with Forbes, Nielsen and Coxswain Magnusson on board. Survey **line 218** was run off Willow Point, where grab **samples 325-326** showed angular clasts of Lake Agassiz sediment and very soft Winnipeg mud, respectively, in 3.8 and 6.3 m of water. The yawl then returned to 'The Mounds' to collect samples of cliff sediment for the USGS study, after which a landing on the south side of Willow Point revealed a section with abundant molluscs in a high gravel berm. Following this, the yawl ran survey **lines 218a-220** off the south side Willow Point barrier and into the lagoon behind. Positioning for all of this work was by non-differential GPS. After completing this work at 1218, the yawl proceeded to Netley Marsh, where shore surveys were run, repeating 1990 and 1994 surveys, at site 8208 on the south shore of the lake west of the navigation channel. Survey **line 221** was run out into the lake, extending the beach profile, using the Geotracer 2000 RTK system for precise differential positioning. The ship steamed north and re-occupied **core site 222** (line SB14, *Namao* 96-900, Fig. 3), anchoring at 1035. A piston core was retrieved at 1101 and the ship weighed anchor at 1120 and steamed east to **core site 221**, (line SB14, *Namao* 96-900, Fig. 3) anchoring at 1148. Once again, a piston core was recovered at 1205. The CCGS *Namao* weighed anchor at 1217 and steamed south to **core site 224** (line SB1, *Namao* 94-900, Fig. 3). The ship anchored at 1428 and a gravity core was obtained at 1442, followed by a piston core at 1459. After completing line 221, the yawl proceeded up the Red River to Selkirk, overtaking CCGS *Namao* along the way, and arrived at the Coast Guard Base about 1730. The ship weighed anchor at 1516 and steamed south into the Red River, arriving at the Selkirk Coast Guard Base at 1807. Core processing on the foredeck during the afternoon continued after the ship was secured until approximately 1900.

On **September 4 (Day 248)**, demobilization of the CCGS *Namao* began. The yawl departed from the Coast Guard Base dock shortly after 0830 with Forbes, Nielsen and Coxswain Magnusson on board. Conditions on the lake were quite rough, but survey **lines 222-227** were run off Grand Beach and Grand Marais. Mud was collected in grab **sample 327**, from 7.1 m water depth off Grand Beach. A landing was made on Stevens Island, the barrier island south of Grand Marais, for shore surveys and sampling. In Selkirk, the shipping container was emptied of all boxes, sorted on the dock and filled with equipment. All navigation equipment was stripped from the bridge and the bridge deck. The accommodation trailer was removed by crane from the boat deck of the ship and all equipment and data boxes were stripped from the trailer. Chapman arrived shortly after 1300 from Halifax and took charge of box packing and stowing boxes back into the shipping container. The yawl returned at 1630 and was stripped of its geophysical and navigation equipment. The packing of the shipping container was completed and the cases remaining on the dock were covered in tarpaulins. The cores were left in the core storage in the hold because the refrigerated core container was not cool.

On **September 5 (Day 249)**, Todd and Chapman departed and shipped geophysical gear and data. The refrigerated container was repaired and the cores were moved to the container. A small device was installed in the container to monitor core temperature during transit to Dartmouth. The ship's crew dismantled the temporary laboratory in the hold. Lewis, Forbes, Thorleifson and Nielsen departed for Winnipeg.

On **September 10 (Day 254)** , the containers were picked up and transported by flat bed truck to Ottawa where the TSD geophysical equipment was unloaded on **September 12 (Day 256)**. The containers were then transported to the Bedford Institute of Oceanography dock in Dartmouth where the equipment container was unloaded on **September 13 (Day 257)**. The refrigerated core container was repaired once again because the compressor installed in Selkirk was inoperative. The temperature logger was recovered from the container on **October 3 (Day 277)**. After the data were downloaded, the device was returned to the container for another three weeks, as cores remained for that time before being transferred finally to cold storage in the GSCA Core and Sample Repository.

4.2 NAVIGATION AND POSITIONING - *B.J. Todd and C.F.M. Lewis*

Equipment description - The satellite-referenced Global Positioning System (GPS) in differential mode was used on board the CCGS *Namao* and the ship's yawl to obtain positions. Much of the equipment was leased for the duration of the survey from Seaforth Engineering Group in Dartmouth, Nova Scotia.

The GPS navigation hardware and software on the CCGS *Namao* consisted of the following:

Magnavox 4200D six channel GPS receiver
STARFIX II differential data correction (single reference station - Duluth, Minnesota)
STARFIX II 5600 receiver
OMNISTAR auxiliary processor
STARFIX II omni-directional antenna (for use in the South Basin)
STARFIX II single horn receiving antenna and LNA/downconverter (for use in the North Basin)
Azimuth controller model 5250
Sperry SR-50 portable gyro compass (for use with the single horn antenna)
Pacific Crest RFM96W transmitter and whip antenna transmitting 35 W
12 volt DC and 24 volt DC power supplies
12 volt battery
IBM-compatible 486 computer
Magnavox 4200CDU software for GPS receiver control
AGCNAV Geological Survey of Canada navigation display/logging software

Procedures and methods - To assist ship's officers in conning the ship for line running and positioning for samples, the Magnavox 4200D GPS receiver and STARFIX II 5600 were installed on the bridge (Fig. 1) A schematic of the DGPS system on the CCGS *Namao* and the yawl is shown in Figure 4. The omni-directional antenna (to receive signals from a suite of GPS satellites) and the Pacific Crest (whip) radio antenna, were mounted on the bridge top forward rail. As well, the omni-directional STARFIX antenna and the gyro-stabilized single horn STARFIX antenna were mounted on steel poles approximately 0.2 m forward of the bridge top aft rail (Fig. 4). These two antennae received signals from a geosynchronous satellite relaying the Duluth, Minnesota reference signal. The omni-directional antenna and the single horn antenna were 14.1 m from the stern (Figs. 1, 4). The single horn antenna was used for the first three days of surveying (Days 222, 225, 226) after which the omni-directional antenna was used to receive the differential corrections.

Differential mode GPS (DGPS) was acquired on the Lake Winnipeg survey using the Duluth reference station. In any survey, three (and preferably four) satellites are required to calculate a differential position. Differential mode improved positional accuracy from 50-70 m (non-differential mode) to 10 m or better. The outputs from the STARFIX system were individual corrections for each satellite observed at Duluth. These data were combined with the satellites observed from the ship using the Magnavox 4200D receiver and were also transmitted via the Pacific Crest radio link to the yawl where the data were combined with the launch's Magnavox 4200D receiver. The corrected output provided time (UTC), latitude, longitude, course over the ground and speed over the ground. These data were recorded at a 5 s interval on the hard disk of the 486 computer.

Geophysical survey lines were drawn on Canadian Hydrographic Service Charts 6248 (1981), 6241 (1982) and 6251 (1986). Way points were calculated from these charts and entered into the computer using AGCNAV. The desired survey line was then displayed on the computer monitor along with actual ship's position obtained from the DGPS receiver. Other information, such as course, speed and range, were also displayed on screen. This combined display enabled the ship's crew to accurately steer along planned geophysical survey lines. The bridge AGCNAV computer forwarded the raw navigation data to a satellite AGCNAV computer mounted in the geophysical lab in order to duplicate the bridge navigation display, and to AGC DIG for data annotation. The Magnavox 4200D receivers also provided NMEA data strings to the sidescan recorder on the ship and the Knudsen sounder on the yawl for data annotation.

Coring sites were determined by first inspecting high-resolution seismic records. For a selected feature on the record, a corresponding day and time were noted. Stored navigation files were then interrogated to find the latitude and longitude corresponding to the selected day and time. The computer display on the bridge was then altered from line-running mode to point mode. Thus the ship could accurately reoccupy a position to deploy the sampling devices.

Operational performance - Based on previous experience gained in 1994, few difficulties were encountered in setting up the hardware and the software on the CCGS *Namao*. Because of difficulties encountered with the omni-directional antenna on the previous survey, this antenna was mounted on a steel post approximately 3 m above the bridge top. Reception with the single cone antenna (mounted approximately 2.5 m above the bridge top) was poor, causing frequent position shifts lasting up to 3 minutes or more. These shifts were more frequent and longer lasting on northerly and westerly headings. A switch was made to the omni-directional antenna on Day 228 resulting in a great improvement in position stability. Only extremely rare spikes occurred in the navigation from this time onward.

Preliminary problems with the Pacific Crest transmitter/receiver were traced to inappropriate baud rate settings on the receiver and transmitter data ports. These were reset to 9600 baud as well as the baud rate for transmitter/receiver communications. Because the yawl operations were often beyond reach of the radio link, the launch's DGPS system was of only occasional use.

During coring operations, the CCGS *Namao* anchored at the coring stations and remained stationary until all cores and equipment were secured on the foredeck. However, inspection of the navigation data collected during coring operations revealed an apparent drift of the recorded ship's position of tens to hundreds of metres, clearly an impossible occurrence. Because drifts of this magnitude were not experienced conning the ship during geophysical data collection, or during steaming to sites selected for coring, it suggested that the DGPS system provided erroneous positional data only while the ship was stationary. This observation was tested further by logging navigation data while the CCGS *Namao* was secured overnight to docks at a number of locations around Lake Winnipeg. Considerable drift was recorded at these sites, confirming the unstable nature of the navigation system while the ship was at rest.

4.3 GEOPHYSICAL SURVEY - *B.J. Todd, B. Chapman and R.A. Burns*

4.3.1 Multi-channel seismic reflection system

Equipment description - The multi-channel seismic reflection profiling system was composed of an Geometrics R24 StrataView seismograph recording signals received from a seismic eel. Power was supplied to the seismograph by a Lambda EWS 300-12 switching regulator DC power supply fed by ship's power. The seismograph contains instantaneous floating point amplifiers with a 32 bit floating point digital signal processor. Preamplifier gain was set at 36 dB with a maximum input signal of 300 mV peak-to-peak. When operating in its marine mode, the seismograph operates with a replace function and an autosave function. These features allow recording and storage of records in less than 5 seconds. Each seismic record consists of 24 channels with 1024 samples per channel at a 0.25 millisecond (ms) sample rate. The record length is 256 ms and the file size is 106 kilobytes. Using a 0.25 ms sample rate provides a recorded bandwidth of 2-1200 Hz with a dynamic range of 104 dB. To avoid clipping the recorded seismic signal, the seismograph used a trigger lockout time of 4.8 seconds that prevented the seismograph from triggering on the Seistec pulse. The Seistec was disabled as the sleeve gun shot was received by the seismograph, and the Seistec was then enabled. The Seistec firing rate was 0.25 seconds.

Within the seismograph is an IBM-compatible computer using an 80486 processor, data storage capacity of 340 megabytes, and 8 megabytes of RAM. A SCSI interface allowed external data storage on a 1 gigabyte drive, thereby allowing storage of a large number of records without leaving the "record" mode on the seismograph. In the evening, seismic data were downloaded from the 1 gigabyte drive to 100 megabyte ZIP disks in an external ZIP drive. Approximately 940 records were stored on each ZIP disk.

The seismic eel consists of 24 receivers spaced at a 5 metre interval (115 m live section) (Fig. 5). Each receiver consists of 2 AQ-16 hydrophones wired in parallel with a 0.5 metre separation. Each hydrophone has a frequency response of ± 0.5 dB from 0.5 Hz to 3 kHz, a sensitivity of -97 dB referenced to 1 V per microbar, a capacitance of 3500 picofarads, and a depth rating of 1828 metres. The output signal from each pair of hydrophones passes into an AQ-300 differential input/output preamplifier. The preamplifier has an input impedance of 30 Mohm, a gain of 20.8 dB with a 20 Kohm resistor installed, a bandwidth of 3 dB points 0.3 Hz to 14 KHz, a current of 750 microamps, a voltage of 8-30 V and a common mode rejection ratio of greater than 80 dB.

The seismic energy source used was a 10 cubic inch sleeve gun operated at an air pressure of 1600 psi. The fore-and-aft offset from the source to the first hydrophone was 10 m; the streamer was towed 3 m to port from the source (Figs. 1, 5). Approximately a 5 ms sleeve gun delay was removed by a trigger. This trigger also masked the Seistec boomer when the sleeve gun was fired at a 5-second interval.

A single-channel feed (channel 3) was supplied to an EPC 8300 graphic recorder to provide quality control on the data and to provide a single-channel sleeve gun record of the geophysical survey lines. The presence of gas in the sediments often obliterated reflections on the Seistec system whereas the sleeve gun and multi-channel eel system was able to record reflectors in such problem areas.

Operational performance - In eight surveying days, 3609 records were obtained (Table 3).

4.3.2 High resolution seismic reflection system

Equipment description - The high resolution seismic reflection system (Seistec) consisted of the following components:

ORE Geopulse power supply (175 joules)
IKB boomer (seismic energy source)
IKB-Seistec line-in-core hydrophone array (seismic energy receiver)
Benthos 3 m external eel (seismic energy receiver)
Master Interval Timing System (MITS)
EPC 9800 graphic recorder for Seistec system
EPC 8300 graphic recorder for
Sony DAT digital magnetic tape recorder

Procedures and methods - The Seistec receiver was towed from the upper deck crane to port from the stern (Figs. 1, 5). The cone houses a seven-element, acceleration-cancelling stick hydrophone array. In spite of the height of the upper deck from the surface of the water, the crane's articulation allowed the tow point of the Seistec to be lowered a few metres to provide smooth towing.

The system was fired at a 0.25 second firing rate controlled by the MITS. Every tenth shot was suppressed to allow the sleeve gun system to fire. This permitted the two seismic systems to operate without their energy source signals being detected on the other system's receiver. (The sleeve gun signal was also recorded on the NSRF eel as shown in the schematic in Figure 7). The ORE power supply was mounted on the stern, protected by the upper deck overhang. The data were displayed on-line using a dual-channel EPC 9800 graphic recorder at two sweep speeds providing, on the same paper output, a record 62.5 ms in length (left channel) and 125 ms in length (right channel). Having two vertical scales of data recorded simultaneously greatly enhances the interpreter's ability to identify features and discriminate real reflectors from noise and system artefacts.

Operational performance - The Seistec high-resolution profiler system worked flawlessly except for a malfunction of the ORE boomer at the northern end of line NB16 near Berens Island on August 15 (Day 228). The boomer was dismantled, repaired and tested while in Berens River over August 17-18 (Days 230, 231). During this time, a spare boomer was flown from GSCA to Winnipeg and brought to the ship by Coast Guard personnel. Water had leaked into the boomer and its performance had degraded to the point that the high frequency content of the signal was almost eliminated. Rough weather and variable towing speeds sometimes degraded the record. Overall, however, the records obtained from this system produced the most detailed, highest-resolution images of the sedimentary sequences from the lake bottom to bedrock. Consequently, coverage by this system on the widely-spaced lines around the lake were given highest priority resulting in the collection of 238 line-kilometres of Seistec profiles (Table 4).

4.3.3 Sidescan sonar

Equipment description - The sidescan sonar system consisted of the following:

Simrad MS992 dual frequency sidescan sonar system
Alden 9315CTP printer

Procedures and methods - The sidescan sonar towfish was towed off the port or starboard bow by a block attached to the crane (Figs. 1, 8). The towfish was lowered to a depth of about 3-4 m below the water surface. The shallow draft of the CCGS *Namao* offered no interference to the system at this depth. The port and starboard side-looking channels were used on the 100 m slant range during the survey, giving both 110 kHz and 330 kHz records displayed on the Alden 9315 printer.

Operational performance - High quality records were obtained throughout the duration of the survey (Table 4). However, the Alden printer often stopped printing and had to be closely monitored. Even with this monitoring, watch keepers had multiple duties in the geophysical laboratory and this did not allow constant monitoring. Therefore, numerous data gaps exist on the sonographs. The cause of the Alden printer failure is unknown.

4.3.4 Digital tape recording

Two methods of data recording were employed during the survey: the eight channel Sony DAT recorder model PC208A, and the four channel AGC DIG data logger (Fig. 8). The DAT was used to record the Seistec data on channels 1, 2 and 3. Channels 4 through 8 were reserved as a backup for data from the Simrad MS992 sidescan sonar. Data were saved to DAT tapes (Table 5).

AGC DIG was used to digitally log Simrad MS992 sidescan sonar data. Channels 1 and 2 logged 110 kHz port and starboard signals, while channels 3 and 4 logged 330 kHz port and starboard sidescan sonar signals. Data were saved on

Exabyte tapes (Table 6).

4.4. CORING AND GRAB SAMPLES - *C.F.M. Lewis and B.J. Todd*

4.4.1 Long cores

Gravity and piston cores were obtained at twenty-two locations throughout the lake at key sites as identified on the 1996 and 1994 geophysical records. The core sites are shown in Figure 3 and the pertinent information is listed in Table 7. The cores were collected to mainly sample the Lake Winnipeg Sequence and the upper part of the underlying Agassiz Sequence at widespread locations; three long cores were obtained specifically to sample the Agassiz sequence in North Basin and four to sample mud-buried paleo-beach deposits in South Basin. The sites were selected on the Seistec profile lines both to enhance interpretation of the geophysical records and to ensure the targets were within reach of the coring equipment. The 1996 cores complement and extend information gleaned from long cores collected in 1994.

Coring systems - The CCGS *Namao*, being designed as a navigational aids tender, is well suited for handling large equipment on the foredeck and for deployment over the side. The vessel is equipped with a 9 m cable boom having a 5 ton primary runner with capability for operating a second runner. The foredeck is approximately 8.5 m by 8.5 m in size with a raised hatch cover in the centre of the deck.

A wide-diameter piston corer and gravity corer were the primary coring tools used on the cruise. These systems and all other equipment were designed and built to be used on designated research vessels as well as ships of opportunity. This simplified the preparation, installation and handling of the corer on the CCGS *Namao*. The piston corer is designed for recovering relatively long cores, and is the tool of choice for sampling sediment sections at several metres depth below the lake floor. However, it is not an ideal tool for sampling the upper metre of sediment; in many cases the piston corer will disturb or bypass this interval entirely. The gravity corer is a complementary tool, for it samples the upper one to two metres with a minimum of disturbance or shortening. On this cruise the mean recovery ratio for all gravity cores is 0.84±0.09, a relatively high value, indicating that most of the uppermost sediment in the Winnipeg Sequence was recovered at the gravity core sites. The recovery ratio is the ratio of length of recovered core to the apparent penetration or length of core pipe showing mud on its exterior surface (Table 7 and Appendix 10.4). In comparison, the recovery ratio for all piston cores is 0.80±0.17. Some of the lesser recovery in the piston cores could be due to bypassing of the uppermost sediment.

Gravity coring - The gravity corer was a Murphy gravity corer (100 kg, 220 lb) consisting of a weighted 2-m long wide-diameter aluminum tube and cutter that accommodated the same plastic core barrel liner as used in the piston corer. The corer was easily assembled on deck, then lifted and lowered into the lakebed, and recovered with a runner and the ship's boom. After some experimentation, the corer was made to perform well by using only two of its four weights, and attaching a plywood collar below the weights to prevent the corer from penetrating too far into the soft lakebed mud. The almost flawless performance of the corer on this cruise was in stark contrast to its singular inability to retain sediment during deployments on the 1994 cruise. The improvement is attributed to the use of a longer barrel (2 m vs. 1.5 m) which allowed the cutter to penetrate more deeply into slightly firmer, more easily retained sediment.

Piston coring - The piston coring system consisted of the following components:

- Corer headweight - modified Alpine corer head (545 kg, 1200 lb) to accept wide-diameter core barrels, described next
- Core barrel - 1.5 m long; 10.8 cm (4.25 inch) inside diameter (ID) with 0.95 cm (0.375 inch) wall thickness
- Couplings - straight for wide-diameter core barrels, secured with set screws
- Core barrel liner - cellulose acetate butyrate of 10.52 cm (4.14 inch) outer diameter (OD) and 9.92 cm (3.904 inch) ID
- Trip arm (trip mechanism)
- Trigger weight (lead weight on a plywood board) and trigger cable that attaches to the end of the trip arm
- Pistons, split and solid types
- Coring cable (1.27 cm diameter, wire, anti-torque lay), terminated with a fiege fitting that attaches to the piston, all of which moves inside the core liner during the coring action

Rigging, deployment and recovery of piston corer - Initially, the coring cable was installed as the primary runner on the *Namao's* boom for use throughout the coring phase of the cruise. At each coring site, the core head was rigged diagonally across the foredeck. Each barrel was installed from the corer headweight downward. As the corer head and protruding barrels were set up, they were kept stable by wooden blocking. Alternately, the barrels and liners were made up first, fitted with a harness, then lifted horizontally with the boom runner and slid (jiggled) into the corer headweight. A maximum barrel length of 9 m was rigged due to space and handling limitations and the limited depth of the water in Lake Winnipeg. A rope was passed through the corer headweight and each barrel and liner as they were inserted. The rope was then used to pull the wire coring cable with its fiege fitting through to the base of the core pipe. The fitting was attached to the piston and both were pushed back into the end of the lowest core barrel. Finally, the core pipe was completed by inserting a multi-fingered, stainless-steel, core retainer and attaching a cutting shoe or cutter.

At the core site, the trigger weight cable was put through a snatch block on the boom's second runner and the free end shackled to the side of the ship. The boom was lifted up until the trigger weight cleared the deck, then the weight was lowered over the side. It was left hanging from the side of the ship for later attachment to the trigger arm. The length of the trigger cable was preset to equal the sum of the length of the core pipe, headweight, and the intended freefall distance, the last being about 3 m.

In deploying the piston corer, the boom's second runner was attached to a lifting ring on the side of the corer headweight. The boom was used to gently lift the headweight and slide the attached barrels through an opening in the starboard rail. The whole system was boomed up and allowed to slide over the edge of the deck until the corer was near vertical with its lower end in the water and its upper end at deck working level. A loop of coring cable equal to the freefall distance was fashioned and lightly tied at the top of the corer headweight. The trip lever mechanism, with a safety pin engaged, was clamped to the cable just above the freefall loop, and the short arm of the trip lever was slipped into a ring at the top of the corer headweight. The trigger-weight line was then attached to the long arm of the trip lever mechanism. The coring cable was tightened to take up the weight of the corer, and the secondary runner was disconnected from the corer headweight. The trip lever mechanism, clamped to the coring cable, now acted as a large double-armed balance. With its point of attachment to the coring cable serving as a fulcrum, the heavy corer hangs from a short arm on one side of the fulcrum and is balanced by the trigger weight hanging from a long arm on the opposite side of the fulcrum. After removing the trip arm safety pin, the corer was moved with the ship's boom away from the side of the ship. It was then lowered to the lake bottom until it triggered. Triggering occurred when the trigger weight settled onto the lakebed, unbalancing the trip lever mechanism, so that the long arm moved up and the short arm down. The corer slipped off the short arm of the trip mechanism to begin its freefall. The triggering was automatic and was signalled by a recoil in the coring cable as the heavy corer started to fall freely. At this signal the winch and boom operator would stop the downward descent of the coring cable. The system was set up to allow the corer and piston to fall together while gathering downward momentum for penetrating the lakebed. Just above the sediment surface, the freefall loop was exhausted and the piston was arrested. The corer continued moving downward, sliding past the piston while coring the lake sediment.

After the coring drive was completed, the piston was pulled up with the coring cable to a stop at the base of the corer headweight. With continued pulling, the corer and its core were withdrawn from the lake bottom and lifted to the ship's side. The reverse order of operations to that described above were used to remove the trigger mechanism and place the core-filled corer on the foredeck. The core liner was then extruded from the core barrels, cut in 1.5 m sections, sealed at the ends, labelled and stored upright in a cool air-conditioned room in the ship's hold.

Upon completion of the cruise, the cores were shipped by road from the Canadian Coast Guard Base in Selkirk, Manitoba to the Bedford Institute of Oceanography (BIO) in Dartmouth, Nova Scotia. They were secured upright in an air-conditioned container and transported on a flatbed truck. A Vemco™ TDR temperature logger was installed in the container. It operated during the trip and while the cores remained in the container at BIO before being moved into the cold storage space at the GSC Sample and Core Repository at BIO. Figure 9 shows the time sequence record of air temperature in the container at 5 minute intervals from **Day 249** (September 5) to **Day 277** (October 3). The record begins with adjustments on **Day 249** (temperature up to about 20°C during initial problems getting the air conditioner working) and extends through **Days 254** to **257** while the container was in transit from Selkirk to Dartmouth (temperatures generally between 8 and 14°C, with a single spike to 19°C when problems were encountered with the power supply). After the container was connected to BIO power on **Day 257**, the temperature was abruptly restored to 8°C and was maintained except during a power failure associated with the passage of Hurricane Hortense on **Days 258** to **259**, a scheduled power outage on **Day 265**, and brief warm spikes associated with opening the container to handle cores at intervals from **Day 268** to **Day 276**. In summary, the cores were generally maintained at 8°C with brief exposure to temperatures up to 21°C and no cooling below 6.4°C.

Since transfer to the GSC Sample and Core Repository, the cores have been maintained at a constant temperature of about 4°C, except when removed to the lab for splitting, logging, and subsampling.

Performance of the piston corer - At the outset, the corer was fitted with a split piston. This device separates after the corer has completed its penetration into the lake sediments. This action has the advantage of reducing suction, tension, and core segmentation when penetration is incomplete and the piston has to be pulled up through a substantial length of unused core pipe, a common condition. The corer performance was monitored by the recovery ratio, the ratio of length of recovered core to the apparent penetration or length of core pipe showing mud on its exterior surface (Appendix 10.5). At the first station, 201, this was 0.875, a satisfactory value, but at the next site, 202, it dropped to 0.657 (Table 7). The average recovery ratio for all sites at which the split piston was used is 0.67±0.09. Despite making all possible adjustments this could not be improved substantially. The split piston was replaced with a solid piston beginning with station 213, and for this core the ratio was 0.953, a substantial improvement (Table 7). The mean recovery ratio for all sites at which the solid piston was used is 0.91±0.14. The reason for the poor performance of the split piston is not clear. One possibility is the piston split prematurely so that during the coring action the lower (separated) part had to be pushed up the pipe by the incoming sediment core. The resulting back pressure on the incoming sediment could have induced core shortening through compaction and bypassing.

4.4.2 Bottom grabs

A van Veen grab sampler capable of recovering a 900-cm^2 surface area of the lakebed was also employed. Two van Veen grab samples (Stations 210, 211) verified the presence of a rippled veneer of coarse sand north of Berens Island (Table 8).

4.5. LIMNOLOGICAL SAMPLING - *L.H. Thorleifson and B.J. Todd*

4.5.1 Biological sampling

Phytoplankton samples consisting of 0.1 litre of surface water treated with a preservative were collected for H. Kling of the Freshwater Institute at 57 stations (Table 9). Lake water was obtained by dipping a rinsed 12 litre plastic pail on a rope near the stern.

Zooplankton net hauls were obtained for A. Salki of the Freshwater Institute at seven sites near the north end of the lake (Table 10). The hauls were completed by lowering a net from the forward deck of the CCGS *Namao* while the ship was on station. The majority of the hauls were completed while the ship was anchored at a core site. Some of the hauls deviated from vertical (Table 10) due to drift of the ship in the wind. Weight was added to the net to reduce this problem. After the net made contact with the bottom for five seconds, it was raised at a rate of about 0.75 to 1 m per second. Contents of the net, including two rinses, were drained into a jar. Recovered plankton were preserved in formaldehyde.

4.5.2 Water sampling

Two sets of water samples were taken for analysis by M. Stainton and R. Hesslein of the Freshwater Institute in Winnipeg. At the 57 sites sampled for phytoplankton, water samples intended for the determination of carbon dioxide partial pressure were collected by placing an evacuated bottle containing a preservative in the sampling bucket and penetrating the stopper with a hypodermic needle. At 20 of these sites (Table 9), a 2 litre water sample was collected and, on the same day, processed on board for a 0.5 litre whole water sample, three filtrations, a 0.3 litre filtrate sample, a scintillation vial of whole water, and a scintillation vial of filtrate.

A carbon dioxide logger set up under stairs at the starboard aft corner of the forward deck was operated for R. Hesslein of the Freshwater Institute during the first three days of the cruise. Data were collected from 1300 CDT until 1445 on 9 August, from 1145 until 1417 on 12 August, and from 1100 until 1500 on 13 August. While the ship was operating at low speed on a geophysical line, a submersible pump was set up to recover water from approximately 0.5 m depth on the starboard side of the forward deck. The water was pumped into a 20 litre bottle through a rubber stopper. An overflow kept the water bottle about two-thirds full. A pump circulated air from the head space of the bottle to a carbon dioxide analyser, and a hypodermic needle penetrating the stopper prevented pressure imbalance. Carbon dioxide data were obtained using a data logger and manual backup. These continuous records designed to monitor diurnal fluctuations will be calibrated using evacuated bottle water samples.

4.5.3 CTD sampling

A total of 10 CTD (Conductivity-Temperature-Depth) casts were undertaken from stations 215 to 224, inclusive. A Seabird Electronics Limited SB19 instrument was used. This instrument contains a SenTek transiometer which measures light attenuation along a 25 cm path length. Plots of temperature versus depth and light transmission versus depth are provided in Appendix 10.2.

4.6. NEAR SHORE SURVEYS - *D.L. Forbes*

Parallel to the scientific program being carried out aboard CCGS *Namao*, shore-zone surveys were undertaken at a suite of sites around the lake. This work was supported by the Namao workboat, a 20-foot (6 m) aluminum Lake Winnipeg 'yawl' (the design in common use as an open fishing boat on the lake). Powered by twin 75 hp outboard motors, the yawl was capable of 33 knots under ideal conditions, but was slow and uncomfortable in rough weather. The yawl was carried on the foredeck of the *Namao* and was put over the side on a daily basis, weather permitting, to operate independently, typically within 2 hours travel from the ship's position. Coxswains were provided from the *Namao*'s crew. At various times during the cruise, Frank Gnitzinger, Brian Sparks, Warren Magnusson, and John Hansen took responsibility for the yawl. In most cases, two scientific staff were also aboard to operate the survey equipment.

Although constrained by wind and by the ship's movements, which were dictated primarily by the shipboard program, the yawl operations were highly successful, completing 128 geophysical survey lines at 17 sites. The yawl also provided a platform for access to the shoreline, whereby onshore surveys were completed at 11 new sites not previously surveyed in 1994 (Forbes and Frobel, 1996). The shore survey program and data will be reported in a subsequent open-file report. In total, 27 grab samples of lake-floor sediments were obtained from the yawl and 33 samples of beach, dune, and cliff deposits were collected onshore. Wood samples for radiocarbon and tree-ring analyses were obtained from drowned forests at four sites (Nielsen, this volume).

4.6.1 Navigation and positioning - *D.L. Forbes, M. Douma, P. Girouard*

The yawl was conned and positioned using satellite navigation based on the Global Positioning System (GPS). A gimbaled ship's compass was also carried for steering purposes.

Three separate GPS systems were employed on the yawl during this cruise.

The ***primary system***, supplied in part by the Geological Survey of Canada (Atlantic) and in part on lease from Seaforth Engineering Group, Dartmouth, Nova Scotia, consisted of the following equipment on the yawl:

Magnavox™ 4200D, 6-channel, GPS receiver and whip antenna
Pacific Crest™ RFM96W, 2 W, radio modem with omnidirectional mobile whip antenna
12 V DC power supply
80486-based notebook computer
Magnavox™ 4200CDU software for GPS receiver control
Geological Survey of Canada AGCNAV navigation display and logging software.

Differential data corrections, relayed from the CCGS *Namao* by radio, were derived from a reference station at Duluth, Minnesota.

The ***second system***, supplied by Terrain Sciences Division, Geological Survey of Canada, Ottawa, consisted of the following equipment on the yawl:

Trimble™ Pathfinder Basic Plus hand-held, 6-channel, GPS receiver with remote antenna
12 V DC power supply;
Trimble™ Pfinder v. 2.53 software

and the following components at the reference station onshore:

Trimble™ Community Base Stn, 12-channel, GPS receiver with L1 geodetic antenna
80386-based portable computer
12 V, 5 A, DC power supply
Trimble™ PFCBS software

The ***third system***, supplied by the Geological Survey of Canada (Atlantic), Dartmouth, Nova Scotia, consisted of the following items aboard the yawl:

Geotracer™ 2000, real-time kinematic (RTK), 12-channel, GPS receiver and ground-plane antenna
Pacific Crest™ RFM96W, 2 W, radio modem with whip antenna
12 V DC power supply
80386-based hand-held computer (control unit)
Pentium-based notebook computer

and the following equipment at the reference station onshore:

Geotracer™ 2000, real-time kinematic (RTK), 12-channel, GPS receiver and ground-plane antenna on tripod
Pacific Crest™ RFM96W, 35 W, radio modem with whip antenna
12 V DC power supply.

Procedures and methods - Differential GPS (DGPS) positioning requires simultaneous logging of satellite signals on the mobile platform (unknown location) and at a fixed and known position, in order to correct for arbitrary errors imposed on the GPS time signals by the US military. Three and preferably four satellites are required for calculation of a differential position and four are needed to obtain elevation data in the RTK system. In the absence of differential corrections, the estimated position may be in error by as much as 300 m, although much better precision was obtained in many cases during this survey program. Depending on the system in use, differential GPS positioning of the yawl was improved to a precision of <10 m (Magnavox™), <5 m (Trimble™), <2 m (Geotracer™ in DGPS mode), and <0.5 m (Geotracer™ in RTK mode). The accuracy was affected by any errors in the estimated positions of the base stations (Table 11).

The Magnavox system provided the navigation display on the yawl. AGCNAV software was installed on the 80486 notebook computer used to log the Magnavox data. This computer was mounted under the windscreen forward of the wheel, with a cardboard sun screen to reduce glare. The screen display showed way points, track run, heading, and other data useful for navigation purposes.

The Trimble™ DGPS system was employed on the yawl for the first two days of the near shore survey program (days 223 and 224) on surveys in the vicinity of Gimli, 'The Mounds' (site 8031 north of Gimli), and Willow Point. The Trimble™ base station was located on the upper bridge deck of the CCGS *Namao* while the ship was tied up for the weekend in Gimli. The geodetic position of the base station antenna was not available, but an average position was determined by 48 hours of continuously recorded position data. Trimble™ base station was also tied to fixed points onshore by an RTK survey on the evening of day 223 and subsequently to the 1997 Trimble™ base station at Willow Point the following year. The difference between the position based on the 1996 CCGS *Namao* coordinates and a 3-day average position in 1997 was 1.8 m in northing and 2.4 m in easting. A position obtained for the 1997 base station based on 8 days of data differed from the 3-day average by 0.9 m in northing and 1.1 m in easting. For the 1996 surveys, GPS positions were logged separately at the base station and on the yawl. DGPS positions were obtained by post-processing in the evening after each survey.

The Geotracer™ RTK system was used in full kinematic mode (centimetre resolution) for onshore surveys and in DGPS mode (metre resolution) on the yawl. Base stations were established onshore on a day-to-day basis at each survey site. Survey control markers (3-inch aluminum caps on rebar) were installed at most base stations. Coordinates for the base stations were taken from non-differential GPS fixes on the base station receiver at the time of setup.

Operational performance - The Magnavox DGPS system was installed on the yawl for all surveys but was fully operational only on days 223-225. After day 225, differential corrections were never reliably received from the CCGS *Namao* and all Magnavox positioning data are therefore treated as non-differential GPS. On several occasions, both the Magnavox and an alternative DGPS system were logged simultaneously. These tests demonstrated errors generally <100 m for the non-differential GPS data and frequently <30 m.

The Trimble™ DGPS system performed reliably during the short time it was available (days 223-224).

The Geotracer™ 2000 system provided the most precise navigation but accuracy was no better than the non-differential fixes obtained for the base stations. In general, the system performed reliably in DGPS mode on the yawl, but range was limited to a few kilometres and signal loss was experienced when high ground intervened, as at the west end of George Island, where the radio modem signal could not be received from the base station located at the east end of the island.

4.6.2 Geophysical surveys - *D.L. Forbes, B. Chapman, M. Douma, E. Nielsen & C.F.M. Lewis*

Geophysical surveys conducted from the yawl included depth soundings, sub-bottom profiling, and sidescan sonar imaging. Table 12 lists survey lines and roll numbers by locality and date. A total of 128 lines were run, ranging in length from a few tens of metres to several kilometres, in water depths from as little as 1 m off numerous beaches to >25 m off The Narrows. The total length of geophysical survey lines obtained with the yawl was 202 km. (Appendix 10.1 provides maps of yawl survey lines).

Procedures and methods -Water depths and sub-bottom profiles were obtained using a Knudsen™ 320M dual-frequency sounder operating at 200 and 28 kHz. The transducers were mounted on an aluminum pipe and fixed over the port side during survey operations. Sound velocity calibration was checked against weighted line measurements. The profiles were recorded graphically on the built-in thermal printer, with day, time, and fix annotations. Depth data were logged simultaneously on a notebook computer using the program GEODOLOG.c (D.E. Heffler, GSCA). This takes NMEA and pseudo-NMEA strings output from the navigation and sounding systems and provides for manual insertion of character strings defining start and end of lines and fix numbers.

Sidescan sonar imagery was acquired using a Klein 421 dual-channel wet-paper recorder and towfish, operating at a nominal frequency of 100 kHz on a typical slant range of 50 m. The fish was towed off the starboard side at shallow depth (1 to 2 m).

Operational performance - The quality of the subbottom profile data was highly dependent on wave conditions. High-resolution sub-bottom records with penetration up to 14 m were achieved in relict Lake Agassiz clays under ideal conditions (see Forbes et al., this volume).

Excellent lakebed images were obtained with the sidescan sonar system at numerous sites in the lake (see Forbes et al., this volume), although the quality was degraded when waves were present. Signal loss was encountered several times and damage was also incurred after the towfish struck a large isolated boulder extending to near the surface in about 6 m of water off the south side of George Island. These problems required extensive repairs to the towfish on two or three occasions.

4.6.3 Bottom sampling - *D.L. Forbes and E. Nielsen*

Twenty-seven lakebed grab samples were obtained at 12 localities, in water depths from 1.7 to 25.2 m (Table 13). These samples were collected with an Ekman box corer and a mini van Veen grab sampler, except for sample 317 off the Saskatchewan River, which was retrieved with the anchor. Sediment types in the samples ranged from pebble gravel, sand, and mud to gritty mud and angular fragments of Agassiz clay. Grain-size analyses of these samples are reported in Appendix 10.8.

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Table 1: *Namao* 96-900 list of Canadian Coast Guard personnel.

Title	Name
Commanding Officer	Rob Aitchison
First Officer	John Hansen
Acting Chief Engineer	Deiter Gnitzinger
Acting First Engineer	Dan Fontaine
Boatswain	Frank Gnitzinger
Oiler	John Bartley
Deckhand	Warren Magnusson
Deckhand	Brian Sparks
Deckhand	Glyn Thomas
Steward	Kelly Cooke
Cook	Kelvin Cooke
Pilot†	Lynn Clemons

† Coast Guard Boston Whaler on Lake Manitoba

Table 2: *Namao* 96-900 list of scientific personnel.

Title and duties	Name	Affiliation	Dates on board
Chief scientist (Geophysical and coring surveys)	B.J. Todd†	GG	August 6- September 5
Scientist (Geophysical and coring surveys)	C.F.M. Lewis†	GSCA	August 8 - September 6
Scientist (Near shore survey)	D.L. Forbes	GSCA	August 10- September 6
Scientist (Near shore survey)	E. Nielsen	MEM	August 10, 12-30, September 2-6
Scientist (Limnological sampling survey)	L.H. Thorleifson†	GSCO	August 9-10, 12-13, 22-27, September 4-6
Technologist (Multi-channel seismic, watch keeping)	R.A. Burns	GSCO	August 6 - 22
Technologist (Yawl navigation and seismics)	M. Douma	GSCO	August 6-13
Technologist (Electronics, watch keeping)	B. Chapman	GSCA	August 6 - 27, September 4
Technologist (Navigation)	P. Girouard	GSCA	August 6 - 22
Technologist (Mechanical, watch keeping)	K. Asprey	GSCA	August 6 - 29
Technologist (Coring)	F. Jodrey	GSCA	August 22- September 6

GG: Geoterra Geoscience
GSCA: Geological Survey of Canada Atlantic
GSCO: Geological Survey of Canada Ottawa
MEM: Manitoba Energy and Mines
† August 31-September 2 on Lake Manitoba

Table 3: *Namao* 96-900 multi-channel seismic data inventory.

Date (August)	Julian day	Line number	Disk number	Directory	File range
9	222	SB12	96-1	SB120092	0092-0591
				SB120592	0592-0772
				SB120001	0001-0091
			96-2	SB120775	0775-1007
				SB121008	1008-1115
12	225	SB13	96-3	SB130001	0001-0499
				SB130500	0500-0939
			96-4	SB130940	0946-1141
				SB131142	1142-1237
				SB131238	1230-1737
			96-5	SB131738	1738-2237
				SB132238	2238-2420
13	226	SB14	96-6	SB140001	0001-0499
				SB140500	0500-0939
			96-7	SB140940	0940-1439
				SB141440	1440-1879
			96-8	SB141880	1880-2379
				SB142380	2380-2819
			96-9	SB142820	2820-3000
14	227	SB15	96-10	SB150001	0001-0499
				SB150500	0500-0939
			96-11	SB150940	0940-1439
				SB151440	1440-1879
			96-12	SB151880	1880-2379
				SB152380	2380-2819
			96-13	SB152820	2820-3319
				SB153320	3320-3759
			96-14	SB153760	3760-3830
15	228	NB16	96-15	NB160001	0001-0499
				NB160500	0500-0939

Date (August)	Julian day	Line number	Disk number	Directory	File range
			96-16	NB160940	0940-1439
				NB161440	1440-1879
			96-17	NB161880	1880-2379
				NB162380	2380-3319
			96-18	NB162820	2820-3319
				NB163320	3320-3759
			96-19	NB163760	3760-4259
				NB164260	4260-4699
			96-20	NB164700	4700-4846
16	229	NB17	96-21	NB170001	0001-0499
				NB170500	0500-0939
			96-22	NB170940	0940-1083
20	233	NB18	96-23	NB180002	0002-4999
				NB180500	0500-0939
			96-24	NB180940	0940-1439
				NB181440	1440-1879
			96-25	NB181880	1880-2379
				NB182380	2380-2819
			96-26	NB182820	2820-3319
				NB183320	3320-3759
			96-27	NB183760	3760-3868
21	234	NB19	96-28	NB190001	0001-0499
				NB190500	0500-0939
			96-29	NB190940	0940-1939
				NB191440	1440-1879
			96-30	NB191880	1880-2379
				NB192380	2380-2819
			96-31	NB192820	2820-3319
				NB193320	3320-3609

Table 4: *Namao* 96-900 paper geophysical records.

Date (August)	Julian day	Line No.	Line length (km)	IKB Seistec		Sleeve gun NSRF eel		Simrad sidescan sonar		Bathymetry	
				Roll No.	Start day/time	Roll No.	Start day/time	Roll No.	Start day/time	Roll No.	Start day/time
					End day/time		End day/time		End day/time		End day/time
9	222	SB12	15.5	1	222/1827			1	222/1648	1	222/1808
					222/1937				222/1930		222/1936
12	225	SB13	24	2	225/1559			2	225/1548	1	225/1559
					225/1917				225/1653		225/1916
								3	225/1657		
									225/1915		
13	226	SB14	27	3	226/1553	1	226/1645	4	226/1553	1	226/1539
					226/1949		226/1949		226/1947		226/1945
14	227	SB15	39.4	4	227/1435	2	227/1435	5	227/1433	1	227/1422
					227/1951		227/1950		227/1724		227/1534
								6	227/1730	2	227/1539
									227/1950		227/1950
15	228	NB16	52.2	5	228/1509	3	228/1513	7	228/1506	2	228/1455
					228/1633		228/2230		228/2148		228/2311
				6	228/1638						
					228/2154						

Date (August)	Julian day	Line No.	Line length (km)	IKB Seistec		Sleeve gun NSRF eel		Simrad sidescan sonar		Bathymetry	
				Roll No.	Start day/time End day/time	Roll No.	Start day/time End day/time	Roll No.	Start day/time End day/time	Roll No.	Start day/time End day/time
16	229	NB17	8.4			4	229/1615	8	229/1612	3	229/1615
							229/1748		229/1742		229/1740
20	233	NB18	36.1	7	233/1347	5	233/1357	9	233/1419	3	233/1352
					233/1930		233/1920		233/1921		233/1920
21	234	NB19	35	8	234/1255	6	234/1253	10	234/1300	3	234/1300
					234/1802		234/1800		234/1432		234/1800
								11	234/1434		
									234/1800		
25	238	NB20	3.7		238/1456						
					238/1530						
29	242	SB21	11.5		242/1504					12	242/1507
					242/1655						242/1654

Table 5: *Namao* 96-900 DAT digital tapes start and stop times.

Tape number	Start time	Stop time	Line Number(s)	File Numbers
1	225 / 1601	225 / 1855	SB13	1-7
2	225 / 1855	226 / 1853	SB13, SB14	8-14
3	226 / 1854	227 / 1630	SB14, SB15	15-21
4	227 / 1630	227 / 1920	SB15	22-25
5	227 / 1920	228 / 1730	SB15, NB16	26-29
6	228 / 1732	228 / 2040	NB16	30-36
7	228 / 2043	229 / 1740	NB16, NB17	37-43
8	233 / 1347	233 / 1640	NB18	44-50
9	233 / 1640	233 / 1925	NB18	51-56
10	234 / 1253	234 / 1602	NB19	56-61
11	234 / 1603	234 / 1800	NB19	62-64

Notes: Channel 1 records the raw IKB Seistec data.
Channel 2 records the filtered (500 Hz to 10 kHz) IKB Seistec data.
Channel 3 records the Seistec trigger.
Channels 4 and 5 record the 110 kHz signal of the Simrad sidescan sonar.
Channel 6 records the Simrad sidescan sonar synchronization signal.
Channels 7 and 8 record the 330 kHz signal of the Simrad sidescan sonar.

Table 6: *Namao* 96-900 AGC DIG digital tapes start and stop times.

Tape number	Start time	Stop time	Line Number(s)	File Numbers
1	222 / 1703	222 / 1850	SB12	1-4†
2	222 / 1851	222 / 1901	SB12	1†
3	222 / 1928	226 / 1945	SB12, SB13, SB14	1-18
4	227 / 1434	227 / 1950	SB15	1-7
5	228 / 1508	228 / 2152	NB16	1-12
6	229 / 1613	233 / 1920	NB17, NB18	1-16
7	234 / 1303	234 / 1800	NB19	1-9

Notes: Channels 1 and 2 record the 110 kHz signal of the Simrad sidescan sonar.
Channels 3 and 4 record the 330 kHz signal of the Simrad sidescan sonar.
† Symbol signifies that no end-of-file was written onto the tape.

Table 7: *Namao* 96-900 coring and large grab sample inventory.

Sample Number	Sample Type	Core Recovery Ratio[1]	Geographic Location	Julian Day / UTC Time	Latitude Longitude	Water Depth (m)[3]	Seistec Line Time
201	2 m gravity corer 9 m piston (split) corer	0.88	western Saskatchewan Basin	235 / 19:36:31 235 / 21:09:14	53° 12.0'N 99° 06.9'W	13	NB9 229 / 2344
202	2 m gravity corer 9 m piston (split) corer	0.66	northwestern Saskatchewan Basin	236 / 17:49:50 236 / 18:32:22	53° 43.2'N 98° 36.2'W	13.6	NB11 231 / 2052
203	2 m gravity corer 9 m piston (split) corer	0.65	central Saskatchewan Basin	237 / 16:12:48 237 / 16:42:43	53° 27.3'N 98° 21.5'W	16.5	NB9 229 / 1558
204	2 m gravity corer 9 m piston (split) corer	0.63	northeastern Saskatchewan Basin	237 / 18:14:15 237 / 18:37:12	53° 34.0'N 98° 06.3'W	15.9	NB9 229 / 1317.5
205	2 m gravity corer 9 m piston (split) corer	0.61	northeastern Saskatchewan Basin	238 / 17:39:18 238 / 18:19:09	53° 34.8'N 98° 04.8'W	15.9	NB20 238 / 1520
206	2 m gravity corer 9 m piston (split) corer	0.64	northeastern Saskatchewan Basin	238 / 19:08:34 238 / 19:37:30	53° 34.6'N 98° 05.3'W	15.9	NB20 238 / 1526.8
207	2 m gravity corer 9 m piston (split) corer	0.64	Cannibal Basin	239 / 14:25:03 239 / 14:55:20	52° 51.6'N 97° 51.2'W	17.1	NB8 227 / 1843.4
208	2 m gravity corer 9 m piston (split) corer	0.54	Berens Basin	239 / 17:40:06 239 / 18:02:38	52° 41.2'N 97° 37.3'W	15.9	NB18 233 / 1600
209	2 m gravity corer 9 m piston (split) corer	0.78	Berens Basin	239 / 19:49:05 239 / 20:11:04	52° 30.9'N 97° 34.8'W	16.5	NB18 223 / 1854.5
210	van Veen grab	—	Berens Basin	239 / 21:28:18	52° 25.5'N 97°26.0'W	15.9	NB17 229 / 1734
211	van Veen grab	—	Berens Basin	239 / 21:36:35	52° 25.5'N 97°25.8'W	15.9	NB17 229 / 1736
212	2 m gravity corer	—	Black Bear Basin	240 / 16:10:38	52° 03.1'N 97°04.1'W	11	NB16 228 / 1815
213	2 m gravity corer 6 m piston (solid) corer	0.95	Black Bear Basin	240 / 17:45:16 240 / 18:22:44	51° 52.4'N 96° 56.5'W	11.9	NB16 228 / 1526.1
214	2 m gravity corer 6 m piston (solid) corer	0.95	Black Bear Basin	240 / 19:20:52 240 / 19:38:12	51° 56.1'N 96° 59.1'W	11.3	NB16 228 / 1624.4

Sample Number	Sample Type	Core Recovery Ratio[1]	Geographic Location	Julian Day / UTC Time	Latitude Longitude	Water Depth (m)[3]	Seistec Line Time
215	2 m gravity corer 9 m piston (solid) corer	1	Washow Bay	241 / 16:17:15 241 / 16:37:58	51° 22.5'N 96° 34.3'W	11.6	SB15 227 / 1945.5
216	2 m gravity corer 6 m piston (solid) corer	1	Deer Island "Channel"	241 / 17:39:43 241 / 18:44:53	51° 17.1'N 96° 37.8'W	11.9	SB15 227 / 1753
217	2 m gravity corer 6 m piston (solid) corer	0.97	Hecla-Black Sill	241 / 20:00:36 241 / 20:20:23	51° 08.0'N 96° 35.1'W	11.1	SB15 227 / 1501.5
218	6 m piston (solid) corer	0.46	Pearson Reef	242 / 18:14:01	50° 56.6'N 96° 40.9'W	10.4	Site survey 242 / 16:08:12
219	2 m gravity corer 6 m piston (solid) corer	1	Pearson Reef	242 / 18:46:16 242 / 19:14:38	50° 56.6'N 96° 41.0'W	10.5	Site survey 242 / 16:09:36
220	2 m gravity corer 9 m piston (solid) corer	1	Pearson Reef	242 / 20:03:44 242 / 20:23:54	50° 56.8'N 96° 40.9'W	10.5	Site survey 242 / 16:41:00
221	2 m gravity corer 9 m piston (solid) corer	0.83	northern South Basin	243 / 15:38:08 247 / 17:05:04	50° 56.1'N 96° 37.0'W	10.4	SB14 226 / 1829
222	2 m gravity corer 9 m piston (solid) corer	0.94	south of Hecla Island	243 / 16:23:42 247 / 16:00:38	50° 56.1'N 96° 44.2'W	10.4	SB14 226 / 1710±5
223	2 m gravity corer 9 m piston (solid) corer	0.88	central South Basin	243 / 18:11:56 243 / 18:30:46	50° 39.4'N 96° 48.3'W	9.8	SB3 220 / 1937
224	2 m gravity corer 9 m piston (solid) corer	0.96	southern South Basin	247 / 19:41:48 247 / 19:58:41	50° 33.0'N 96° 47.2'W	8.5	SB1 216 / 1930

1. Core recovery ratio = core length / apparent penetration; see Appendix 10.4 for lengths of apparent penetration and recovered core.
2. Refer to Section 4.4 for description of cores and sampler.
3. Datum for water depth is lake level at the time of sounding. The lake level is given as metres above sea level in Appendix 10.4.

Table 8: *Namao* 96-900 grab sample description.

Sample Number	Sample Type	Geographic Location	Notes
210	van Veen grab	Berens Basin	
211	van Veen grab	Berens Basin	

Table 9: *Namao* 96-900 phytoplankton and water sampling.

Site	Location	Latitude	Longitude	Julian Day	Time UTC	Weather	Air temp. (° C)	Water temp. (° C)	Filtered
W1	Red River mouth	50° 27.7458'	96° 48.0636'	222	1730	partial cloud, breeze	22	21.5	yes
W2	southern South Basin	50° 29.6262'	96° 44.1474'	222	1820	sunny, calm	19.8	22	no
W3	Grand Marais	50° 31.6308'	96° 39.9768'	222	1910	sunny, dead calm	20.5	23.1	yes
W4	Elk Island	50° 49.9662'	96° 34.8990'	225	1600	sunny, breeze	22.2	20.9	yes
W5	Elk Island	50° 48.6192'	96° 32.3118'	225	1635	sunny, breeze	21.1	21.6	no
W6	Elk Island	50° 47.4426'	96° 31.0560'	225	1657	sunny, calm	23.6	21.8	no
W7	Elk Island	50° 45.4920'	96° 29.1888'	225	1735	sunny, calm	20.8	21.9	yes
W8	Elk Island	50° 46.9134'	96° 30.4866'	225	1800	sunny, breeze	21.1	22	no
W9	Elk Island	50° 48.6186'	96° 32.1408'	225	1830	sunny, breeze	20.3	22	no
W10	Elk Island	50° 50.0874'	96° 34.1364'	225	1900	sunny, breeze	20.2	22.3	no
W11	Hecla Island	50° 56.1288'	96° 49.9218'	226	1610	overcast, wind	16.4	19.3	yes
W12	Hecla Island	50° 56.1240'	96° 45.6462'	226	1655	overcast, wind	17.2	19.4	no
W13	Hecla Island	50° 56.1318'	96° 40.9650'	226	1745	partial overcast, wind	16.3	19.7	no
W14	Black Island	50° 56.1240'	96° 36.7122'	226	1832	partial overcast, wind	17.5	19.8	no
W15	Black Island	50° 56.1258'	96° 32.1006'	226	1930	overcast, wind	17.3	19.7	yes
W16	Grand Rapids	53° 12.8039'	99° 03.6493'	236	1420	partial cloud, breeze	18.1	17.1	yes
W17	Selkirk Island	53° 24.2843'	98° 52.9430'	236	1535	thin cloud, breeze	20.4	17.4	no
W18	northern North Basin	53° 35.7647'	98° 42.2367'	236	1650	very thin cloud, breeze	20.6	16.9	no
W19	northern North Basin	53° 41.1223'	98° 37.2405'	236	1725	sunny, breeze	21.5	17.5	yes
W20	northern North Basin	53° 43.2685'	98° 36.2409'	236	1805	partial cloud, breeze	19.6	17.6	no
W21	northern North Basin	53° 40.2746'	98° 21.4386'	236	1915	thin cloud, wind	17.6	17.3	no
W22	northern North Basin	53° 38.2787'	98° 11.5704'	236	2005	thin cloud, wind	18.3	16.9	no
W23	Warren Landing	53° 35.4844'	97° 57.7549'	236	2115	thin cloud, wind	19.1	17.6	yes
W24	Warren Landing	53° 36.7016'	97° 56.8920'	237	1425	sunny, wind	19.1	17.7	yes
W25	Warren Landing	53° 32.3816'	98° 08.1919'	237	1520	sunny, wind	18.3	17.1	no
W26	North Basin	53° 27.2761'	98° 21.5463'	237	1630	sunny, breeze	19.2	17.3	no
W27	North Basin	53° 30.7391'	98° 13.5101'	237	1735	sunny, breeze	20.5	18.4	no

Site	Location	Latitude	Longitude	Julian Day	Time UTC	Weather	Air temp. (° C)	Water temp. (° C)	Filtered
W28	Warren Landing	53° 34.0342'	98° 06.2775'	237	1830	sunny, breeze	23	18	yes
W29	Warren Landing	53° 36.7016'	97° 56.8920'	237	1930	sunny, wind	22.4	18.9	yes
W30	Warren Landing	53° 36.7016'	97° 56.8920'	238	1430	partial cloud, calm	15.5	17.3	yes
W31	Warren Landing	53° 34.3167'	98° 05.7931'	238	1530	thin overcast, calm	16.8	16.8	no
W32	Warren Landing	53° 35.2232'	98° 03.0682'	238	1625	thin overcast, calm	16.9	17.6	no
W33	Warren Landing	53° 34.8297'	98° 04.8072'	238	1735	thin overcast, calm	18.5	17.4	yes
W34	Warren Landing	53° 34.8297'	98° 04.8072'	238	1830	thin overcast, slight breeze	16.3	17.4	no
W35	Warren Landing	53° 34.6074'	98° 05.3626'	238	1930	thin overcast, slight breeze	19.1	17.4	no
W36	Spider Islands	53° 30.0038'	97° 57.0907	238	2030	thin overcast, slight breeze	18.9	18	no
W37	Spider Islands	53° 19.7700'	97° 47.1196'	238	2130	thin overcast, breeze	19.7	18.7	no
W38	eastern North Basin	53° 04.5579'	97° 42.5391'	238	2255	partial cloud, breeze	18.1	18.5	no
W39	eastern North Basin	52° 57.5685'	97° 41.2881'	238	2330	partial cloud, breeze	18.3	18.3	yes
W40	George Island	52° 51.0731'	97° 36.3514'	239	15	thin overcast, slight breeze	19.9	18.7	no
W41	George Island	52° 47.8957'	97° 40.4722	239	1325	sunny, breeze	19.5	18	yes
W42	George Island	52° 51.5710	97° 51.2409'	239	1425	sunny, calm	21.2	17.4	no
W43	George Island	52° 49.7521'	97° 48.7484'	239	1525	sunny, calm	18.3	17.2	no
W44	south of George Island	52° 41.2115'	97° 37.3787'	239	1630	sunny, calm	18	19.2	no
W45	south of George Island	52° 41.1596'	97° 37.3362'	239	1730	sunny, calm	17.3	18.1	yes
W46	south of George Island	52° 40.0069'	97° 37.0134'	239	1830	sunny, breeze	17.8	18	no
W47	south of George Island	52° 30.8557'	97° 34.7347'	239	1930	sunny, breeze	17.8	18.2	no
W48	south of George Island	52° 30.8144'	97° 34.7084'	239	2030	thin overcast, wind	19.7	18.4	no
W49	Berens Island	52° 25.4595'	97° 24.3013'	239	2135	sunny, wind	20.6	19.1	no
W50	Berens Island	52° 21.9838'	97° 10.8639'	239	2230	sunny, wind	20.3	18.9	no
W51	Cox	52° 15.7078'	97° 11.2708'	240	1435	sunny, strong wind	16.4	18.9	yes
W52	Jackhead	52° 06.1545'	97° 05.8478'	240	1525	thin overcast, strong wind	19.8	17.7	no
W53	Jackhead	51° 58.8472'	97° 00.8653'	240	1635	sunny, wind	18.3	18.4	no
W54	north of the Narrows	51° 52.3866'	96° 56.5578'	240	1730	sunny, wind	19.7	18.9	yes
W55	north of the Narrows	51° 52.4620'	96° 56.4986'	240	1830	sunny, breeze	21.4	18.9	no
W56	north of the Narrows	51° 56.1104'	96° 59.1218'	240	1930	sunny, breeze	22.5	18.4	no

Site	Location	Latitude	Longitude	Julian Day	Time UTC	Weather	Air temp. (° C)	Water temp. (° C)	Filtered
W57	north of the Narrows	51° 49.5060'	96° 54.5349'	240	2030	sunny, breeze	22.1	18.8	yes

Table 10: *Namao* 96-900 zooplankton sampling.

Site	Location	Latitude	Longitude	Julian Day	Time UTC	Weather	Air temp. (° C)	Water temp. (° C)	Depth (m)	Deviation
Z1	Selkirk Island	53° 21.8351'	98° 55.2270'	236	1519	thin cloud, breeze	20.4	17.4	14.3	10°
Z2	northern North Basin	53° 32.5502'	98° 45.2345'	236	1629	very thin cloud, breeze	20.6	16.9	14.8	5°
Z3	northern North Basin	53° 43.2685'	98° 36.2409'	236	1800	partial cloud, breeze	19.6	17.6	13.4	0°
Z4	Warren Landing	53° 35.9235'	97° 59.9259'	236	2104	thin cloud, wind	19.1	17.6	17.4	0°
Z5	central North Basin	53° 27.2761'	98° 21.5463'	237	1625	sunny, breeze	19.2	17.3	16.5	0°
Z6	Warren Landing	53° 34.0349'	98° 06.2898'	237	1846	sunny, breeze	23	18	15.8	20°
Z7	Warren Landing	53° 34.8297'	98° 04.8072'	238	1745	thin overcast, calm	18.5	17.4	15.8	0°

Table 11: *Namao* 96-900 yawl navigation log and base station positions

Day	Date	Locality	System	Method	Base reference[1]	Adopted easting[2] (m)	Adopted northing[2] (m)
223	Aug 10	Gimli	Trimble	DGPS	*Namao*	642799	5610696
224	Aug 11	Gimli	Trimble	DGPS	*Namao*	642799	5610696
225	Aug 12	Elk Island	Magnavox	DGPS?	*Namao*	underway	underway
226	Aug 13		*no survey*				
227	Aug 14	Observation Pt	Magnavox	GPS	*none*		
228	Aug 15	Berens Island	Magnavox	GPS	*none*		
229	Aug 16		*no survey*				
230	Aug 17		*no survey*				
231	Aug 18	Berens Island	Geotracer	DGPS	GSC-310	612193	5797931
232	Aug 19	George Island	Geotracer	DGPS	GSC-322	593224	5852826
233	Aug 20	George Island	Geotracer	DGPS	GSC-322	593224	5852826
234	Aug 21		*no survey*				
235	Aug 22	Saskatchewan River	Magnavox	GPS	*none*		
236	Aug 23	Limestone Pt	Magnavox	GPS	*none*		
237	Aug 24	Playgreen Lake	Geotracer	DGPS	CHS-8402	572136	5957188
238	Aug 25	Spider Islands	Magnavox	GPS	*none*		
239	Aug 26	George Island-Marchand Point	Magnavox	GPS	*none*		
240	Aug 27		*no survey*				
241	Aug 28	Black Bear Island- The Narrows	Magnavox	GPS	*none*		
242	Aug 29		*no survey*				
243	Aug 30	South Basin core search	none	DR	*Namao*	underway	underway
244	Aug 31	Sans Souci	Geotracer	DGPS	GSC-325	646536	5587669
245	Sept 1		*no survey*				
246	Sept 2	Balaton	Geotracer	DGPS	GSC-326	643955	5646343
247	Sept 3	Willow Point-Netley Marsh	Magnavox	GPS	*none*		
247	Sept 3	Netley Marsh	Geotracer	DGPS	1990 rebar	653520	5585157
248	Sept 4	Grand Beach-Grand Marais	Magnavox	GPS	*none*		

1. GSC numbers refer to GSC caps on shore survey control points. CHS number refers to cap on hydrographic control point (Kettle Island).

2. UTM Zone 14 (NAD 83).

Table 12. Namao 96-900 yawl Geophysical records

Date (August-September)	JD	Locality	Line no.	Start time (UT)	End time (UT)	Line length (km)	GPS mode	Knudsen sounder roll no.	Klein sidescan roll no.	Line length (km)
10	223	Gimli north	100	1615	1632	1.4	DGPS	1	1	
			101	1633	1656	1.4	DGPS	1	1	
			102	1656	1710	0.8	DGPS	1	1	
			103	1710	1725	0.8	DGPS	1	1	
			104	1725	1747	1.0	DGPS	1	1	
			105	1747	1758	0.8	DGPS	1	1	
			106	1911	1921	0.5	DGPS	1	1	
			107	1921	1929	0.6	DGPS	1	1	
			108	1929	1936	0.5	DGPS	1	1	
			109	1937	1944	0.5	DGPS	1	1	
			110	1946	1958	0.8	DGPS	1	1	9.1
11	224	Willow Point	111	1431	1504	7.6	DGPS	2	2 & 3	
			112	1508	1535	2.9	DGPS	2	3	
			113	1540	1546	0.7	DGPS	2	3	
			114	1551	1601	5.0	DGPS	2	3	
			115	1605	1611	0.8	DGPS	2	3	
			116	1615	1623	0.9	DGPS	2	3	
			117	1630	1635	0.6	DGPS	2	3	
			118	1640	1650	1.5	DGPS	2	3	19.9
12	225	Elk Island	119	1652	1709	2.2	DGPS	3	4	
			120	1710	1720	1.4	DGPS	3	4	
			121	1721	1736	1.9	DGPS	3	4	
			122	1737	1740	0.4	DGPS	3	4	
			123	1741	1751	1.3	DGPS	3	4	
			124	1752	1807	1.8	DGPS	3	4	
			125	1810	1820	1.3	DGPS	3	5	
			126	1823	1825	0.3	DGPS	3	5	
			127	1828	1837	1.7	DGPS	3	5	
			128	1837	1846	1.0	DGPS	3	5	
			129	1849	1912	2.4	DGPS	3	5	
			130	1913	1957	4.9	DGPS	3	5	
			131	1958	2002	0.5	DGPS	3	5	20.9
14	227	Observation Point	132	1511	1531	1.2	GPS	4	6	
			133	1532	1536	0.3	GPS	4	6	
			134	1537	1543	0.5	GPS	4	6	
			135	1544	1556	1.0	GPS	4	6	
			136	1558	1610	1.0	GPS	4	6	
			137	1611	1617	0.5	GPS	4	6	
			138	1619	1625	0.5	GPS	4	6	5.0
15	228	Berens Island	139	1651	1654	0.4	GPS	5	7	
			140	1659	1715	2.0	GPS	5	7	
			141	1717	1720	0.4	GPS	5	7	
			142	1721	1727	0.6	GPS	5	7	
			143	1728	1748	2.6	GPS	5	7	

			144	1749	1756	0.7	GPS	5	7	
			145	1759	1801	0.2	GPS	5	7	
			146	1835	1842	0.6	GPS	5	7	
			147	1843	1851	0.7	GPS	5	7	
			148	1856	1911	2.3	GPS	5	7	
			149	1912	1917	0.7	GPS	5	7	
			150	1918	1926	0.7	GPS	5	7	
			151	1936	1950	1.8	GPS	5	8	
			152	1951	2000	1.3	GPS	5	8	
15	228	Berens Island (continued)	153	2001	2006	0.7	GPS	5	8	
			154	2010	2015	0.3	GPS	5	8	
			155	2016	2017	0.1	GPS	5	8	
			156	2018	2043	2.1	GPS	5	8	18.3
18	231	Berens Island	157	1739	1755	1.1	DGPS	6	9	
			158	1822	1836	1.9	DGPS	6	9	21.3
19	232	George Island	159	2001	2012	0.9	DGPS	7	10	
			160	2013	2027	1.1	DGPS	7	10	
			161	2033	2045	1.2	DGPS	7	10	
			162	2046	2051	0.3	DGPS	7	10	
			163	2052	2102	0.8	DGPS	7	10	
20	233	George Island	164	1544	1552	1.3	DGPS	8		
			165	1612	1620	0.8	DGPS	8		
			166	1623	1629	1.0	GPS	8		
			168	1925	1953	3.1	DGPS	8		
			169	1954	2022	3.0	DGPS	8		13.6
22	235	Saskatchewan River	170	1636	1706	2.5	GPS	9	11	
			171	1800	1853	8.7	GPS	9		
			172	1854	1859	0.6	GPS	9		
			173	1905	2000	7.9	GPS	9		
			174	2043	2055	1.9	GPS	9		
			175	2100	2109	1.2	GPS	9		
			176	2109	2114	0.7	GPS	9		
			177	2114	2116	0.2	GPS	9		
			178	2116	2119	0.4	GPS	9		
			179	2119	2121	0.4	GPS	9		
			180	2121	2125	0.6	GPS	9		
			181	2125	2136	1.8	GPS	9		
			182	2137	2143	0.7	GPS	9		27.4
23	236	Limestone Point	183	1850	1928	5.0	GPS	10	12	
			184	1929	1943	2.0	GPS	10	13	
			185	1943	1947	0.4	GPS	10	13	
			186	1947	1957	1.2	GPS	10	13	
			187	2002	2013	2.0	GPS	10		
			188	2026	2101	5.8	GPS	11		
			189	2103	2107	0.6	GPS	11	13	
			190	2108	2115	1.0	GPS	11	13	18.0
24	237	Playgreen Lake	191	1635	1651	2.5	DGPS	12	14	
			192	1921	1942	2.6	DGPS	12		
			193	1850	1910	2.3	DGPS	12		

			194	1822	1835	1.6	DGPS	12		8.9
25	238	Spider Islands	195	1630	1705	4.1	GPS	13	15	4.1
26	239	Marchand Point south	196	1519	1533	1.4	GPS	14		1.4
28	241	The Narrows	197	1639	1653	1.5	GPS	15	16	
			198	1653	1711	1.6	GPS	15	16	
			199	1717	1730	1.4	GPS	15	16	
			200	1751	1806	1.4	GPS	15	16	
			201	1806	1813	0.6	GPS	15	16	
			202	1854	1857	0.4	GPS	15	16	
			203	1902	1910	1.2	GPS	15	16	
			204	1911	1930	2.5	GPS	15	16	10.6
31	244	Sans Souci	205	1826	1832	0.4	DGPS	16	17	
			206	1832	1838	0.4	DGPS	16	17	
			207	1838	1844	0.3	DGPS	16	17	
			208	1844	1910	1.9	DGPS	16	17	
			209	1910	1917	0.6	DGPS	16	17	
			210	1917	1933	1.4	DGPS	16	17	
			211	1933	1955	2.0	DGPS	16	17	7.0
2	246	Balaton Beach	212	1846	1856	1.2	DGPS	17	18	
			213	1901	1904	0.2	DGPS	17	18	
			214	1910	1915	0.5	DGPS	17	18	
			215	1916	1919	0.3	DGPS	17	18	
			216	1920	1924	0.5	DGPS	17	18	
			217	1925	1931	0.6	DGPS	17	18	3.3
3	247	Willow Point	218	1421	1429	0.7	GPS	18		
			218a	1642	1649	0.6	GPS	18		
			219	1649	1714	1.9	GPS	18		
			220	1714	1718	0.2	GPS	18		3.4
3	247	Netley Marsh 8208	221	2030	2054	2.0	DGPS	18	19	2.0
4	248	Grand Beach	222	1625	1640	0.9	GPS	19	20	
			223	1702	1714	1.1	GPS	19	21	
			224	1714	1726	1.2	GPS	19	21	
			225	1729	1747	2.1	GPS	19	21	
			226	1747	1759	1.5	GPS	19	21	
			227	1802	1813	1.1	GPS	19	21	8.0
										202.3

Table 13: *Namao* 96-900 yawl nearshore grab sample inventory

Sample no.	Day	Location	Sampler	Material	Setting	Date	Latitude	Longitude	Water depth[1] (m)
96900 -301	224	Gimli	Ekman	brown silty clay	shoreface	Aug 11	50° 37.96'N	96° 58.52'W	5.8
-302	224	Gimli	Ekman	pebbles	nearshore	Aug 11	50° 38.17'N	96° 58.89'W	2.4
-303	224	Gimli	Ekman	sand & pebbles	shoreface	Aug 11	50° 38.16'N	96° 58.78'W	5.9
-304	224	Gimli	Ekman	mud	shoreface	Aug 11	50° 38.13'N	96° 58.40'W	6.1
-305	224	mounds	Ekman	mud clasts & pebbles	nearshore	Aug 11	50° 40.75'N	96° 59.51'W	2.8
-306	224	mounds	Ekman	same (no sample)	nearshore	Aug 11	50° 40.67'N	96° 59.72'W	1.8
-307	224	mounds	Ekman	stiff clay	nearshore	Aug 11	50° 40.56'N	96° 59.68'W	1.7
-308	224	mounds	Ekman	burr. m clasts & dolt p	shoreface	Aug 11	50° 40.69'N	96° 59.31'W	3.3
-309	231	Berens Island	Ekman	angular mud clasts	shoreface	Aug 18	52° 19.17'N	97° 21.74'W	4.8
-310	233	George Island	Ekman	brown medium sand	nearshore	Aug 20	52° 49.00'N	97° 37.67'W	2.7
-311	233	George Island	Ekman	brown f.-m. sand	shoreface	Aug 20	52° 48.95'N	97° 37.65'W	5.1
-312	233	George Island	Ekman	trace fine sand (no sample)	shoreface	Aug 20	52° 48.84'N	97° 37.57'W	9.0
-313	233	George Island	Ekman	silty clay	shoreface	Aug 20	52° 48.64'N	97° 37.52'W	13.3
-314	233	George Island	Ekman	yellow fine sand	nearshore	Aug 20	52° 49.18'N	97° 37.09'W	2.8
-315	233	George Island	Ekman	angular mud clasts	shoreface	Aug 20	52° 49.28'N	97° 37.08'W	5.1
-316	235	Saskatchewan River	Ekman	clayey silt & tr. sand	shoreface	Aug 22	53° 12.42'N	99° 13.84'W	10.5
-317	235	Saskatchewan River	anchor	pebbly silty sand	shoreface	Aug 22	53° 12.45'N	99° 13.93'W	9.7
-318	237	Playgreen Lake	Ekman	fine sand	nearshore	Aug 24	53° 47.08'N	97° 55.24'W	2.7
-319	237	Playgreen Lake	Ekman	sandy mud	channel	Aug 24	53° 46.72'N	97° 56.57'W	5.2
-320	238	Spider Islands	van Veen	gritty mud	shoreface	Aug 25	53° 28.10'N	97° 44.42'W	11.4

-321	241	The Narrows	van Veen	(no sample)	basin ramp	Aug 28	51° 43.44'N	96° 54.95'W	25.2
-322	241	The Narrows	van Veen	pea gravel	basin ramp	Aug 28	51° 45.67'N	96° 51.68'W	21.1
-323	244	Sans Souci	van Veen	angular mud clasts	nearshore	Aug 31	50° 25.49'N	96° 56.15'W	2.2
-324	246	Balaton Beach	van Veen	silty mud & pc gravel	shoreface	Sept 2	50° 56.94'N	96° 56.57'W	3.3
-325	247	Willow Point	van Veen	angular mud clasts	shoreface	Sept 3	50° 36.71'N	96° 57.91'W	3.8
-326	247	Willow Point	van Veen	soft mud	shoreface	Sept 3	50° 36.95'N	96° 57.62'W	6.3
-327	248	Grand Beach	van Veen	mud	shoreface	Sept 4	50° 34.04'N	96° 37.82'W	7.1

1. Water depths relative to lake level at time of sampling.

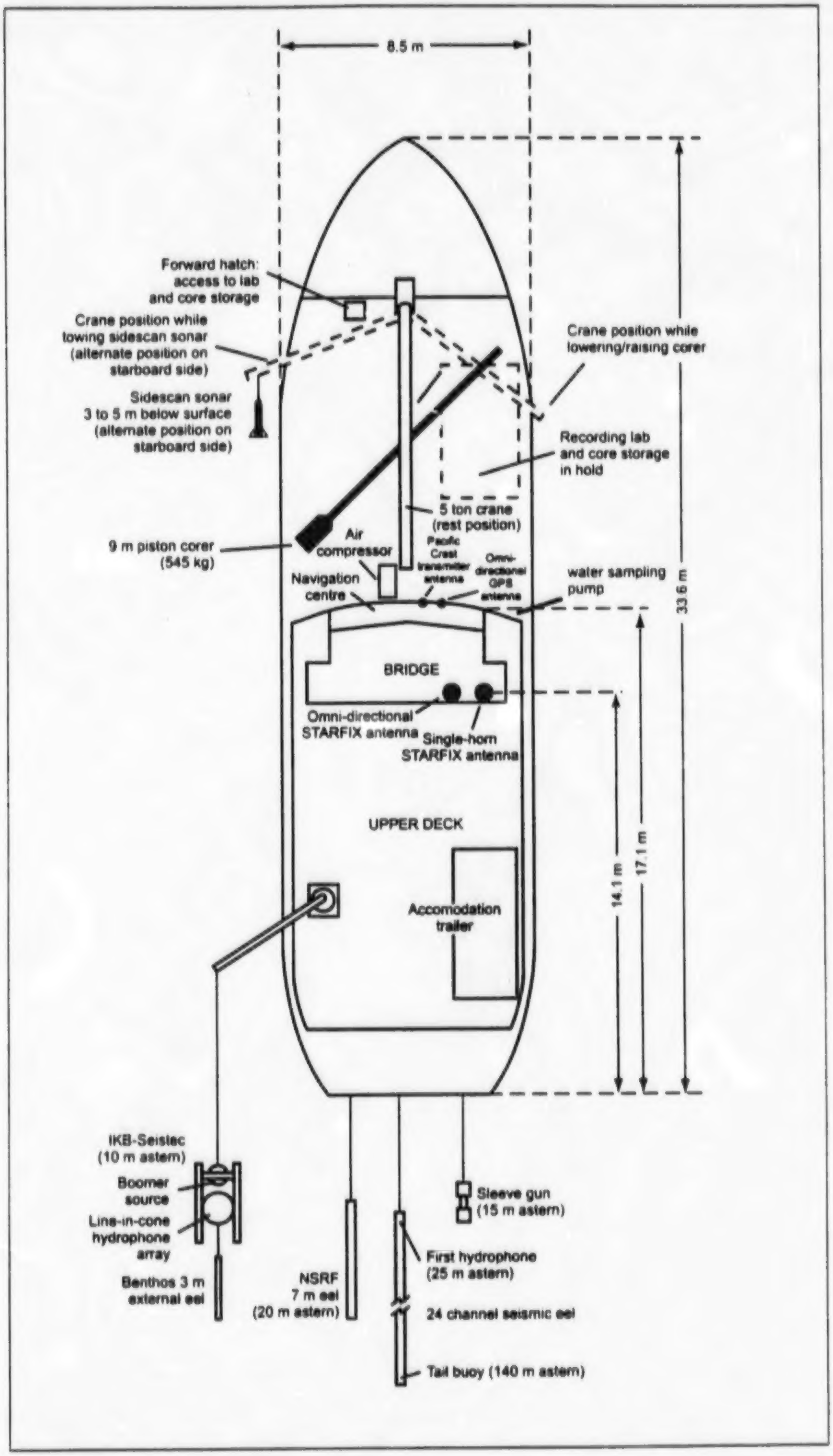
8.5 m
Forward hatch: access to lab and core storage
Crane position while towing sidescan sonar (alternate position on starboard side)
Crane position while lowering/raising corer
Sidescan sonar 3 to 5 m below surface (alternate position on starboard side)
Recording lab and core storage in hold
5 ton crane (rest position)
9 m piston corer (545 kg)
Air compressor
Pacific Crest transmitter antenna
Omni-directional GPS antenna
Navigation centre
water sampling pump
33.6 m
BRIDGE
Omni-directional STARFIX antenna
Single-horn STARFIX antenna
UPPER DECK
Accomodation trailer
14.1 m
17.1 m
IKB-Seistec (10 m astern)
Boomer source
Line-in-cone hydrophone array
Benthos 3 m external eel
NSRF 7 m eel (20 m astern)
Sleeve gun (15 m astern)
First hydrophone (25 m astern)
24 channel seismic eel
Tail buoy (140 m astern)

Figure 1. Layout of scientific equipment on CCGS *Namao*.

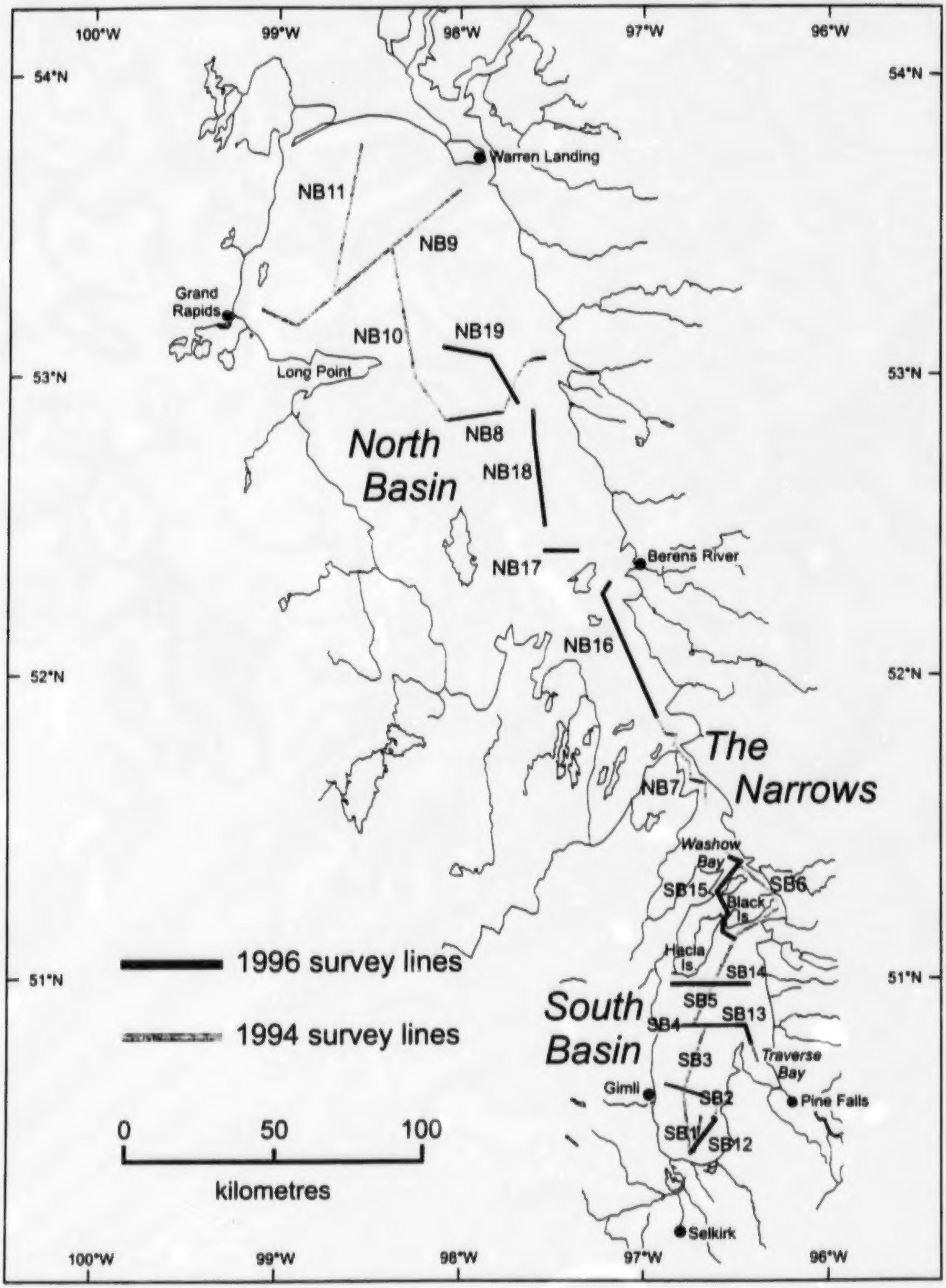
100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
Warren Landing
NB11
NB9
Grand Rapids
NB10
NB19
Long Point
North Basin
NB8
NB18
NB17
Berens River
NB16
The Narrows
NB7
Washow Bay
SB15
SB6
Black Is.
Hecla Is.
SB14
SB5
SB13
SB4
South Basin
SB3
Traverse Bay
Gimli
SB2
Pine Falls
SB1
SB12
Selkirk
1996 survey lines
1994 survey lines
0
50
100
kilometres

Figure 2. Geophysical survey lines collected in Lake Winnipeg in 1994 and 1996.

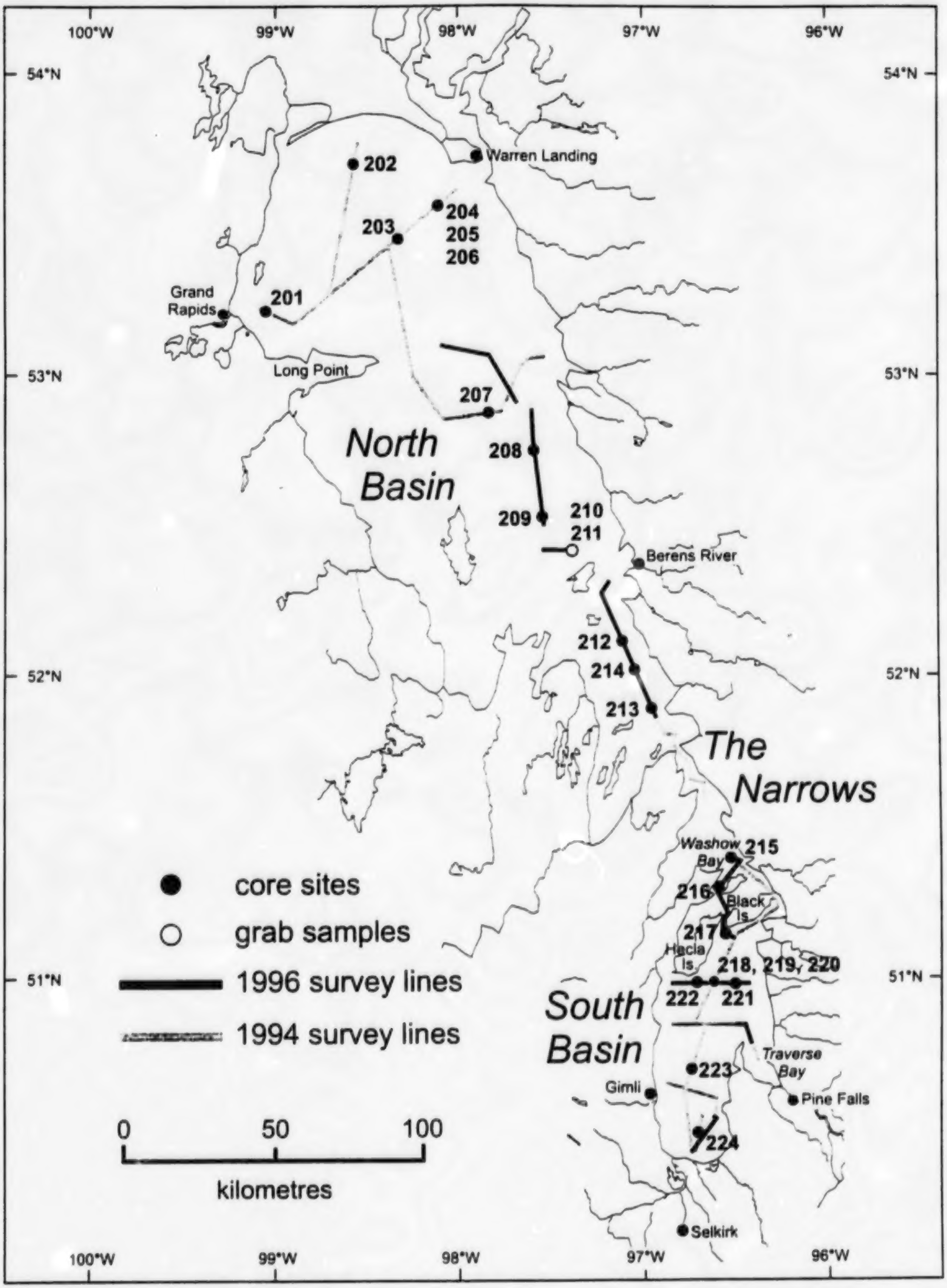
100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
Warren Landing
202
204
205
206
203
201
Grand Rapids
Long Point
207
North Basin
208
209
210
211
Berens River
212
214
213
The Narrows
Washow Bay
215
216
Black Is.
217
Hecla Is.
218, 219, 220
222
221
South Basin
Traverse Bay
223
Gimli
Pine Falls
224
Selkirk
core sites
grab samples
1996 survey lines
1994 survey lines
0
50
100
kilometres

Figure 3. Core and grab sample sites occupied during *Namao* 96-900.

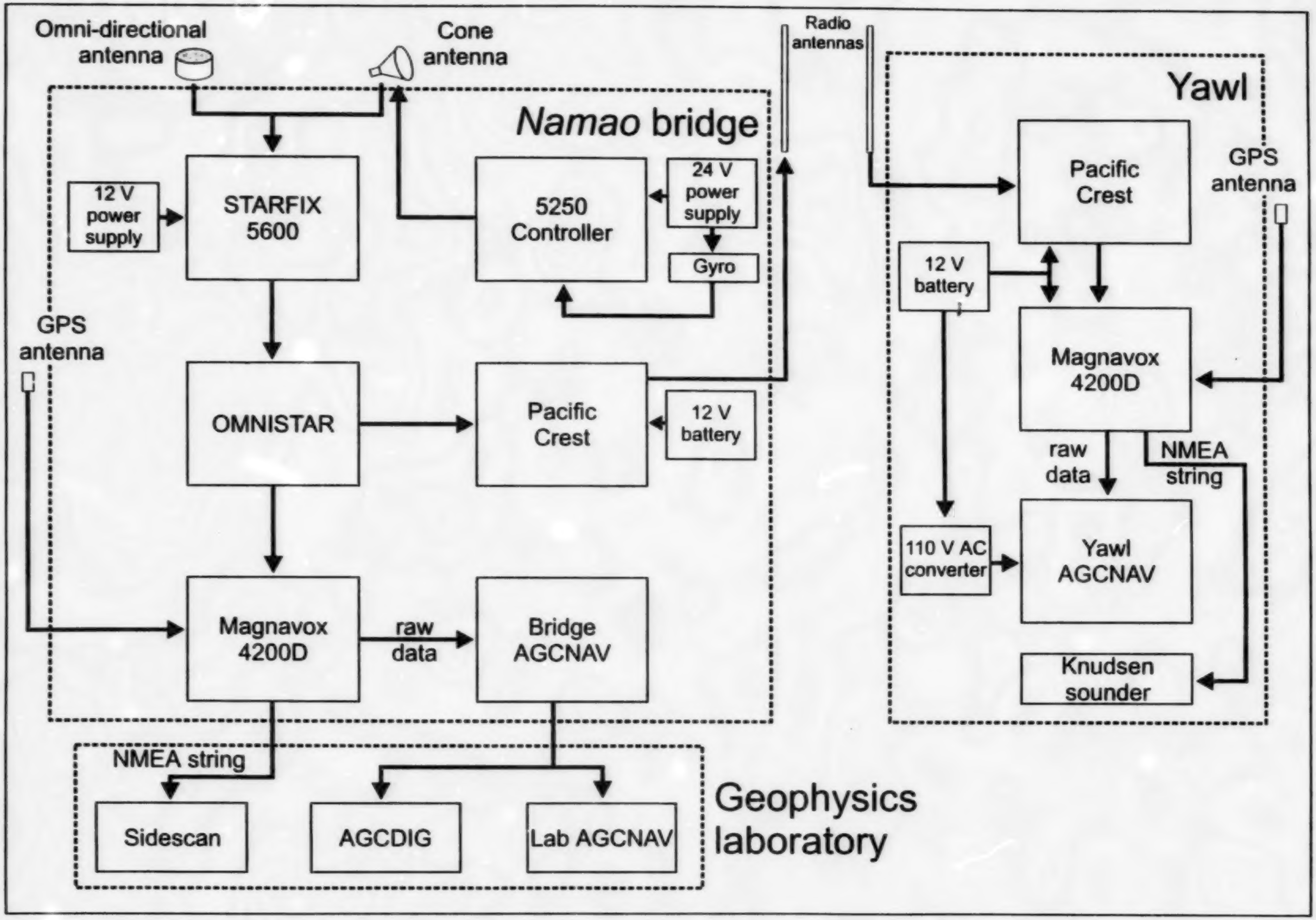
Omni-directional antenna
Cone antenna
Radio antennas
Yawl
Namao bridge
12 V power supply
STARFIX 5600
5250 Controller
24 V power supply
Gyro
GPS antenna
OMNISTAR
Pacific Crest
12 V battery
Magnavox 4200D
raw data
Bridge AGCNAV
Pacific Crest
GPS antenna
12 V battery
Magnavox 4200D
raw data
NMEA string
110 V AC converter
Yawl AGCNAV
Knudsen sounder
NMEA string
Sidescan
AGCDIG
Lab AGCNAV
Geophysics laboratory

Figure 4. Schematic of DGPS navigation systems on the CCGS *Namao* and the yawl.

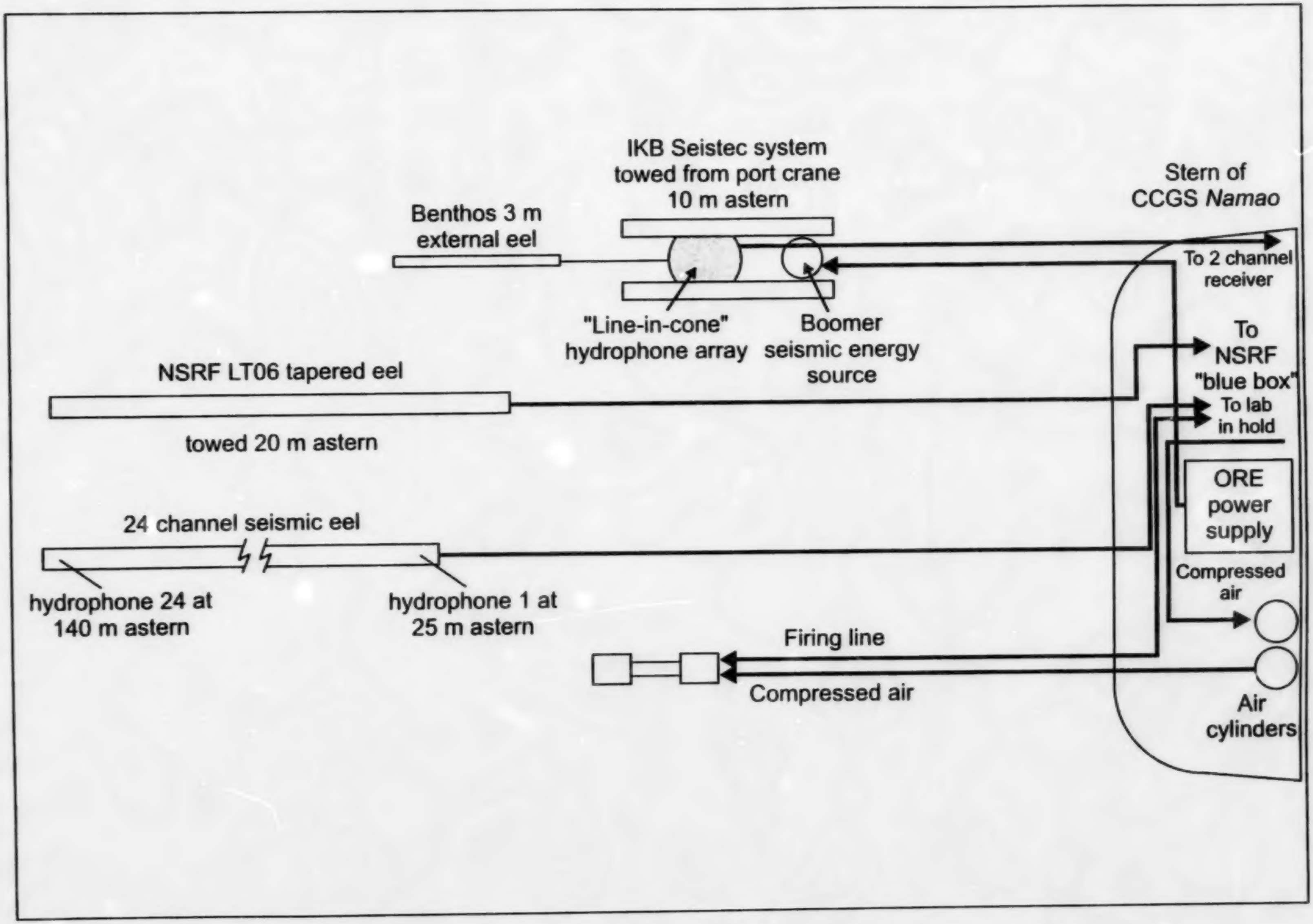
IKB Seistec system
towed from port crane
10 m astern
Stern of
CCGS *Namao*
Benthos 3 m
external eel
To 2 channel
receiver
"Line-in-cone"
hydrophone array
Boomer
seismic energy
source
To
NSRF
"blue box"
NSRF LT06 tapered eel
To lab
in hold
towed 20 m astern
ORE
power
supply
24 channel seismic eel
Compressed
air
hydrophone 24 at
140 m astern
hydrophone 1 at
25 m astern
Firing line
Compressed air
Air
cylinders

Figure 5. Seistec, NSRF eel and multi-channel seismic eel towing setup astern of the CCGS *Namao*.

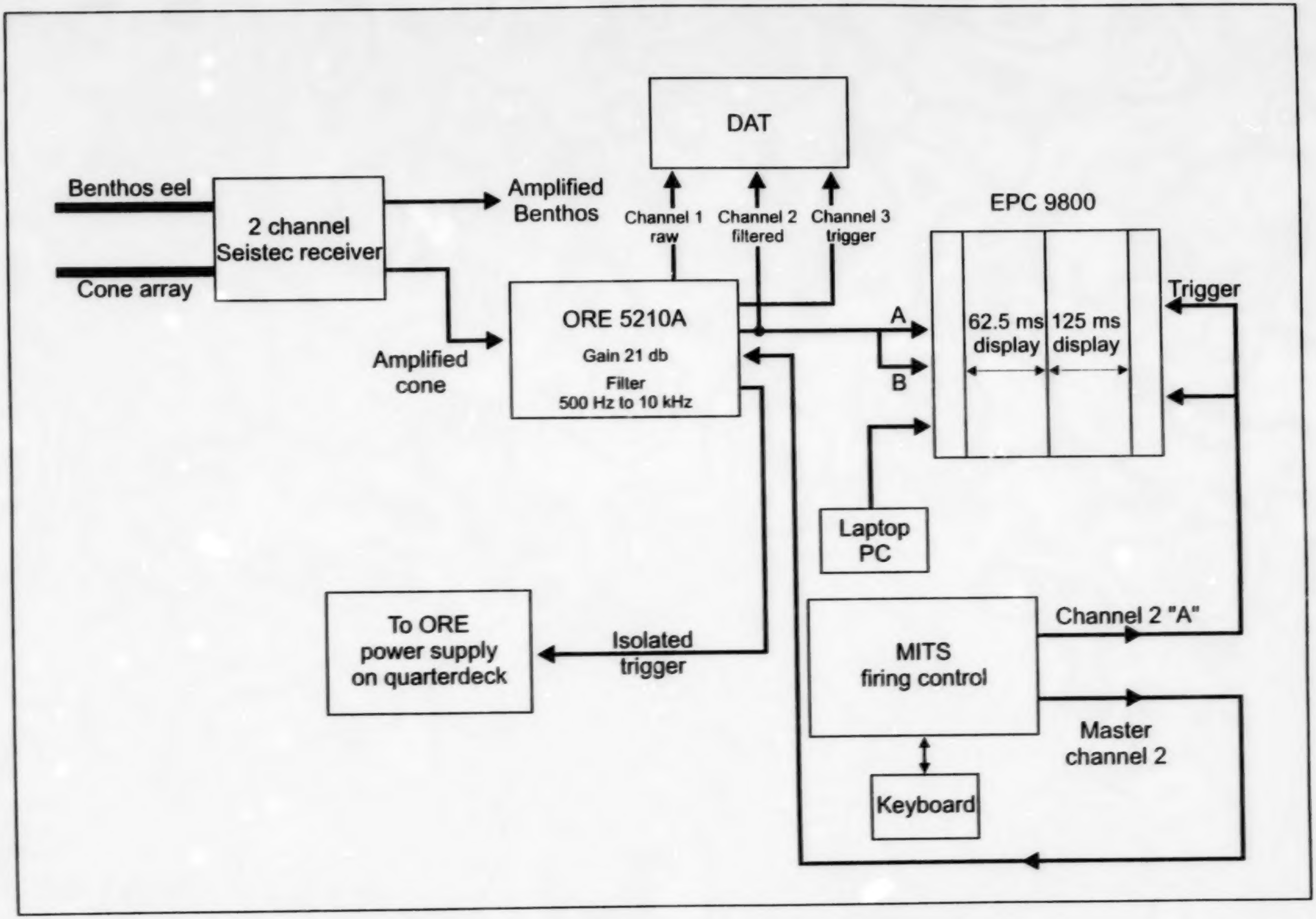
Benthos eel
Cone array
2 channel Seistec receiver
Amplified Benthos
Amplified cone
DAT
Channel 1 raw
Channel 2 filtered
Channel 3 trigger
ORE 5210A
Gain 21 db
Filter
500 Hz to 10 kHz
EPC 9800
62.5 ms display
125 ms display
A
B
Trigger
Laptop PC
To ORE power supply on quarterdeck
Isolated trigger
MITS firing control
Channel 2 "A"
Master channel 2
Keyboard

Figure 6. Schematic of IKB-Seistec equipment setup on CCGS *Namao*.

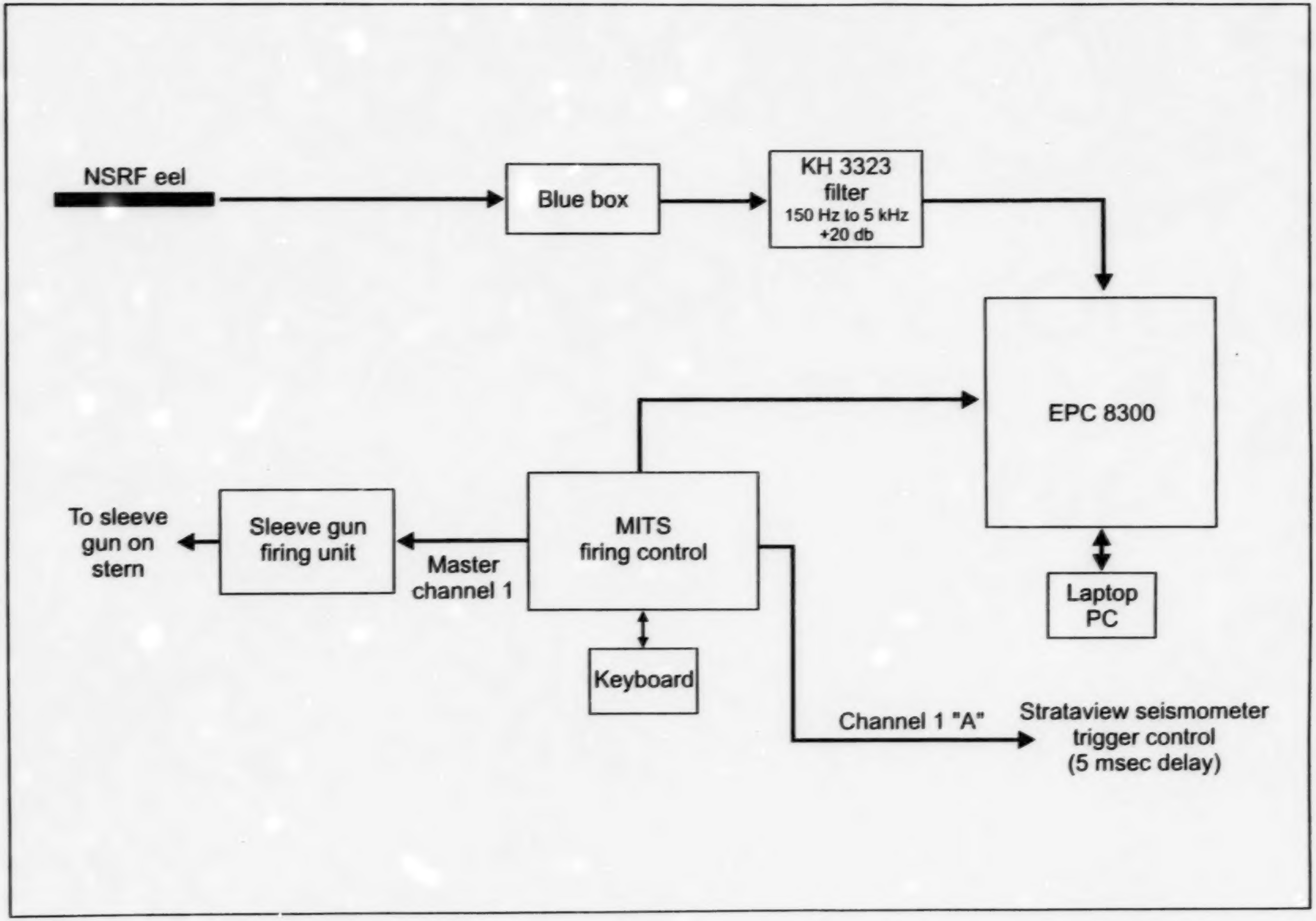
NSRF eel
Blue box
KH 3323
filter
150 Hz to 5 kHz
+20 db
EPC 8300
Laptop
PC
MITS
firing control
Keyboard
Sleeve gun
firing unit
Master
channel 1
To sleeve
gun on
stern
Channel 1 "A"
Strataview seismometer
trigger control
(5 msec delay)

Figure 7. Schematic of NSRF eel and sleeve gun setup on CCGS *Namao.*

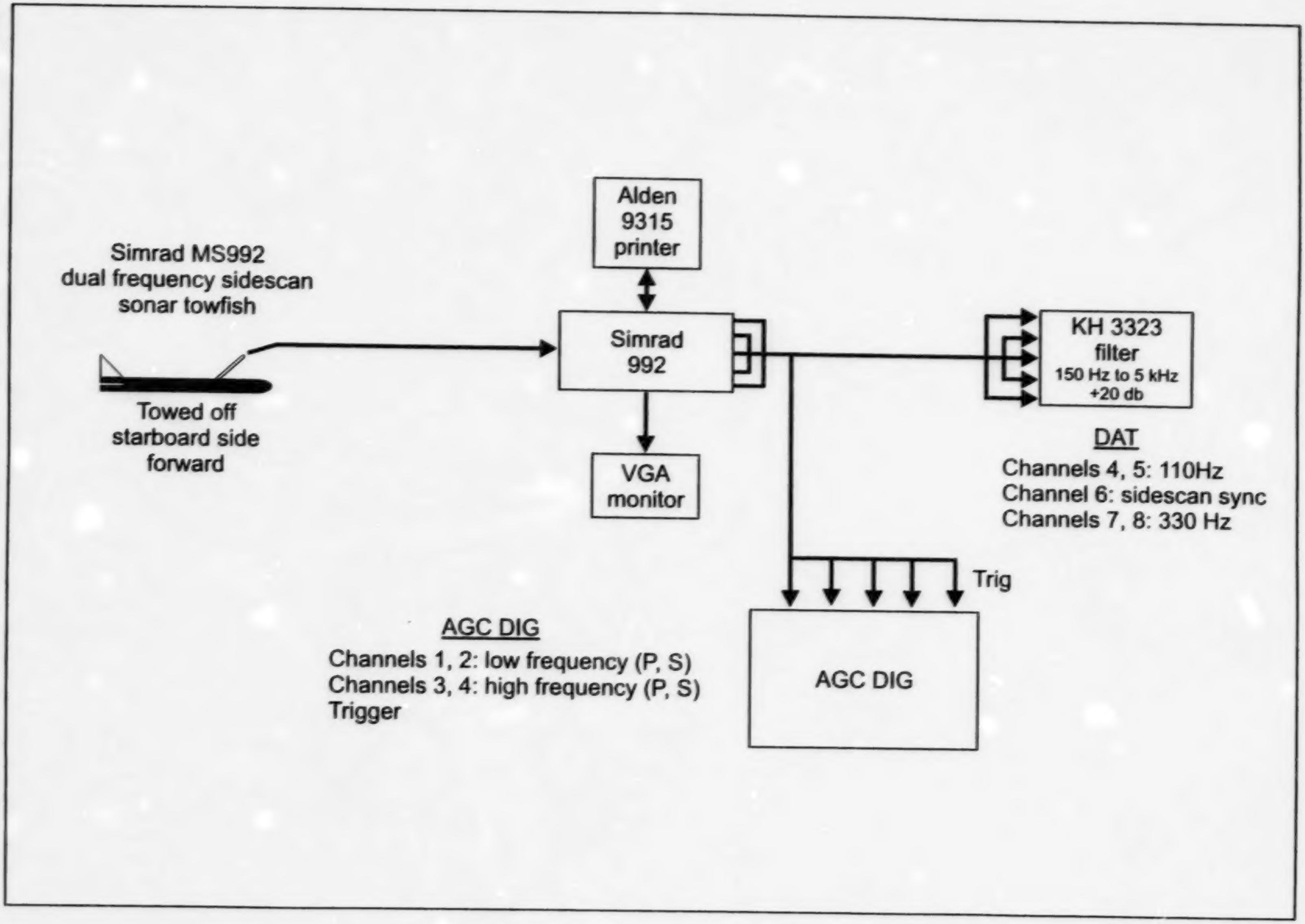
Simrad MS992
dual frequency sidescan
sonar towfish
Towed off
starboard side
forward
Alden
9315
printer
Simrad
992
VGA
monitor
KH 3323
filter
150 Hz to 5 kHz
+20 db
DAT
Channels 4, 5: 110Hz
Channel 6: sidescan sync
Channels 7, 8: 330 Hz
Trig
AGC DIG
AGC DIG
Channels 1, 2: low frequency (P, S)
Channels 3, 4: high frequency (P, S)
Trigger

Figure 8. AGC DIG and Sony DAT digital recording setup on CCGS *Namao*.

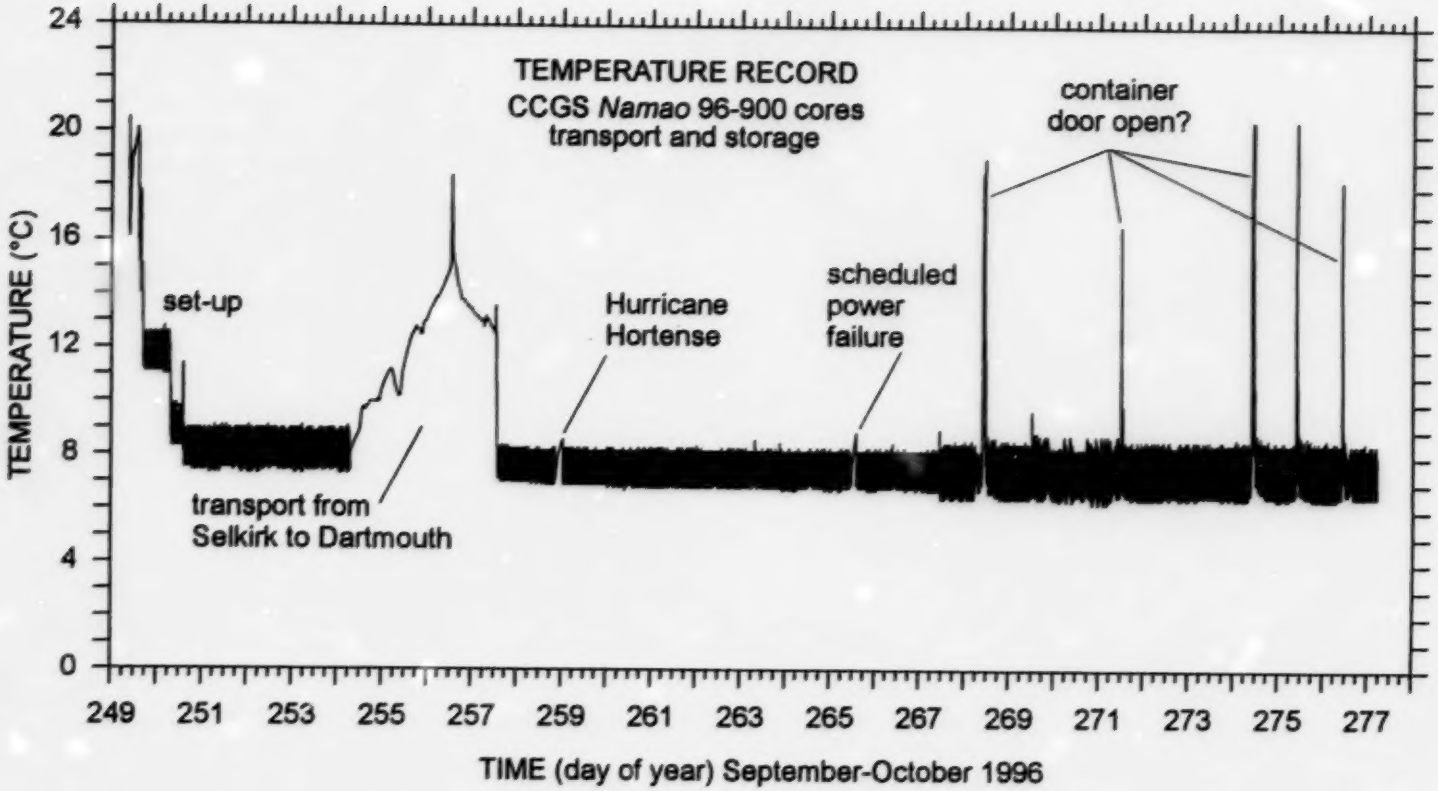

Figure 9. Temperature record of CCGS Namao cores during transport from Manitoba to Nova Scotia.

5. Geophysical survey results

5.1 Seismostratigraphy and lakebed morphology

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INTRODUCTION

During 1996 field operations on Lake Winnipeg, the network of high-resolution seismic reflection profiles in the lake, initiated in 1994, was expanded to provide an almost complete longitudinal transect along the axis of the lake and representative east-west transects across the North and South basins (Fig. 2 of Todd et al., this volume). These surveys were supplemented in 1996 by 28 kHz subbottom profiling in nearshore waters. In some cases, these small-boat surveys extended further into the lake, locally intersecting or overlapping with the high-resolution seismic reflection lines. Sidescan sonar imagery of lakebed morphology was obtained along almost all seismic reflection lines run with CCGS *Namao* and most of the 28 kHz profiles run with the *Namao* workboat known as the 'yawl'.

An introduction to the seismostratigraphy of Lake Winnipeg was presented in Todd and Lewis (1996) and Todd et al. (1997). An expanded discussion can be found in the journal paper by Todd et al. (1998). The purpose of this report is to present examples of lakebed sediment profiles obtained in 1996, including a selection of records from all parts of the lake and from Playgreen Lake on the outlet drainage to the Nelson River (Fig. 1). The records are chosen to illustrate a range of depositional environments and seismostratigraphic facies, including examples that might not otherwise be published in subsequent journal articles. Where particularly relevant, we present a few examples of sidescan sonar imagery of the lakebed morphology and surficial sediments. Where appropriate, reference is also made to relevant cores and grab samples, data for which can be found in Appendices 10.4 and 10.7.

METHODS

The records presented below were obtained using one of two subbottom profiling systems, as follows:

- the IKB Seistec high-resolution seismic reflection system, operating at frequencies of 2 to 8 kHz, deployed from CCGS *Namao*;
- the Knudsen 320M dual-frequency echosounder, operating at 28 and 200 kHz, deployed from the 'yawl'.

The sidescan sonar records were obtained with two systems:

- a Simrad MS992 dual-frequency sidescan system, operating on 100 m slant range at frequencies of 110 kHz and 330 kHz, deployed from CCGS *Namao*;
- a Klein 421 single-frequency sidescan sonar, operating typically on 50 or 100 m slant range at approximately 100 kHz, deployed from the 'yawl'.

The IKB Seistec system is described in more detail by Simpkin and Davis (1993), Todd and Lewis (1996), and Todd et al. (1998). The Knudsen 320M echosounder produced 28 kHz subbottom profiles, which were recorded in hard copy on the built-in thermal printer. Both the high-frequency (200 kHz) and low-frequency (28 kHz) data were also recorded digitally for bathymetric analysis. Further details, including information on positioning, can be found in the cruise narrative (Todd et al., this volume). Track plots for examples illustrated and discussed below can be found in Appendix 10.1 (this volume). Details of the 'yawl' tracks are shown on page-size plots (Maps 1-1 to 1-15). An overview of the entire data set and details of *Namao* tracks are shown in large-format maps on the accompanying CD-ROM (Maps 1 to 3).

RESULTS

Playgreen Lake channel- 'yawl' lines 191 to 194

North of Kettle Island in Playgreen Lake (Fig. 1), a pattern of sounding lines was run across and along the channel downstream from Warren Landing. Lines 192 to 194 were cross profiles, extending over broad shallow flats on each side of the channel, and line 191 was run approximately along the channel axis.

The long profile (Fig. 2A) is smoothly varying in places, slightly rough in others, and highly irregular in short sections. The depths along the profile range from <4 m to a maximum of 9 m. The maximum chart depths in the area are 10.4 m just north of Kettle Island and 12.2 m about 2 km to the southeast (Canadian Hydrographic Service, 1988). The bottom is highly reflective, with little acoustic penetration, except in areas of slightly rough bottom and in a short section immediately past the end of line 191, near the cross-over with line 192, where there is a brief record of almost 4 m penetration into conformably stratified (draped) sediments typical of Agassiz Sequence deposits (far right in Fig. 2A).

The cross profiles, represented here by line 194 (Fig. 2B), show an irregular channel section with a narrow thalweg cut to depths as great as 9 m, bounded on each side by broad, shallow, subaqueous flats with depths from >2.5 m on the northeast (right side of channel in Fig. 2B) to 1.5 m or less on the southwest (left side in same figure). These flats support a heavy growth of aquatic vegetation, which accounts for the high level of acoustic noise in the water column, in contrast to the very clean record in the channel. The channel bed is irregularly terraced at depths between about 4.3 and 5.5 m on each side of a deeper asymmetric thalweg. Much of the channel floor is highly reflective, with no subbottom reflections, except locally where the system penetrated up to 4 m into the channel bed. Dipping reflections beneath each side of the channel axis in the profile illustrated (Fig. 2B) are most readily interpreted as Agassiz Sequence deposits.

Grab sample 319 from the intersection of lines 191 and 192 (EOL191 in Fig. 2A) consisted of mixed sand and mud with a median size of 70 µm (48% sand and 3.2% gravel). Grab sample 318 from the shallow subaqueous flats at the northeast end of line 194 consisted of fine sand with median size of 206 µm and mean of 91µm (79% sand and 1.0% gravel).

Northeast corner of North Basin including Spider Islands shoreface- east end of *Namao* line NB9, 'yawl' line 195

A Seistec profile was obtained by *Namao* along the east end of line NB9, running northeast toward Warren Landing, in the vicinity of core 105 (Fig. 1). This 1994 example is included here to illustrate typical acoustic stratigraphy in the deeper water of the North Basin. In the vicinity of core 105, this profile (Fig. 3) shows about 1 m of weakly reflective, horizontal to slightly irregular, stratified sediments of the Winnipeg Sequence, interpreted as Lake Winnipeg muds, overlying an acoustic unconformity truncating a varied succession of conformably stratified deposits of the Agassiz Sequence. The acoustic basement, interpreted as glacially scoured bedrock of Precambrian age, has an irregular relief of at least 22 m in the illustrated section, the deepest point lying more than 29 m below the lakebed (about 45 m below mean lake level). The present mean lake depth in this area is about 16 m and the unconformity cutting Lake Agassiz sediments (hereafter called the Agassiz Unconformity (AU)) is therefore at a depth of about 17 m.

The Agassiz Sequence deposits in the North Basin have been subdivided into three distinctive parts, as defined by Todd and Lewis (1996). These are (Fig. 3):

- an Upper Reflective Interval (URI) consisting of an upper reflective portion and a lower less reflective component;
- a Middle Reflective Interval (MRI) defined by a prominent reflective horizon near the top overlying a nearly transparent interval up to 13.5 m thick in the section illustrated; and
- a Lower Reflective Interval (LRI) representing a thinner, more reflective component at the base of the Agassiz Sequence.

The irregular basement relief and conformably stratified nature of the Agassiz Sequence leads to significant stratigraphic variability at the level of the AU. In the section illustrated here, the unconformity cuts the sequence at levels ranging from low in the MRI to high in the URI.

About 25 km southeast of core 105 along the northeast shore of the lake, a Knudsen 28 kHz sounder profile was obtained along a line running in to the transgressive barrier beach and dune complex at Spider Islands (Fig. 1; Forbes, this volume). A compilation of the bathymetric data with topographic surveys also conducted at the site (Fig. 4) shows the active barrier with dunes at least 14 m high, the beach, bar, and nearshore sand profile with diminishing slope lakeward, terminating in about 5 to 6 m water depth, a little over 300 m off the beach (distances are measured from a benchmark (GSC-321) established in the backshore at the time of this survey). Outside the base of the nearshore slope, the bottom is a more or less irregular erosion surface (the developing AU) forming an almost horizontal terrace inside the first of two prominent rock outcrops. Beyond the outcrop, the erosional surface deepens lakeward from 6 to 7 m at 2 km offshore to 13.4 m at 4.4 km from the beach. The lakebed on the inner part of the section is quite rough, but the surface unconformity becomes relatively smooth in depths greater than 8 m (Fig. 5). Furthermore, this apparently graded erosional surface is ramped up against the lakeward side of the outer outcrop in a manner consistent with a nearshore profile. The Agassiz Sequence sediments show differential erodibility on the inner profile (out to 8 m water depth), but there is very little relief where the erosion surface is better developed at depth. The sediments exposed at this erosion surface appear to belong mostly to the URI, although part of the MRI may be exposed between 6 and 8 m depth (left side of Fig. 5).

The absence of Winnipeg Sequence muds at 13.4 m off Spider Islands and the thin (1 m) cover of Winnipeg deposits over a similar unconformity in the area of core 105 are consistent with an interval of significantly lower lake level in this northeast corner of the North Basin, close to the original outlet control at Warren Landing. If we assume that sidescan sonar evidence for ripple bedforms and irregular morphology on the present Spider Islands shoreface at depths down to about 8 m is indicative of the depth of active erosion today, then a lake-level lowering of at least 8 m would be required to generate the Agassiz Unconformity in 16 m present depth at core 105. If we assume a shallower active depth of 6 m, consistent with the base of the nearshore at Spider Islands (Forbes, this volume), then a lake-level lowering of at least 10 m is suggested. This almost certainly requires an element of climatic control in addition to isostatic tilting.

Western North Basin off Saskatchewan River outlet- west end of *Namao* line NB9, 'yawl' lines 171 to 173

Core 201 was located on the basis of the 1994 line NB9 in a position off the present Saskatchewan River outlet near Grand Rapids. The primary objective was to sample Winnipeg Sequence sediments to find evidence and chronological control for diversion of the Saskatchewan River into the lake, an event estimated by McMartin (this volume) to have occurred about 4.7 ka. During the coring operation in 1996, 28 kHz Knudsen profiles were obtained running out the river channel into the lake at the outer channel marker (CN2) and then along the westward extrapolation of line NB9 to overlap with the 1994 *Namao* survey in the vicinity of the core site (Fig. 3 in Todd et al., this volume).

The channel extends some 2.5 km into the lake and is bounded by a broad shoal to lakeward (Fig. 6A). At this location, the channel floor is about 11 m deep and reasonably flat. At the side of the channel there is a steep bank 0.9 m high, beyond which the lakebed rises across a broad levee-like mound or ridge and then eastward in a broadly convex profile, cresting at a depth of about 9.7 m. The bottom is highly reflective, both within the channel and over the nearby shoal, which could be interpreted as a wave-worked prodelta deposit of the Saskatchewan River. On the other hand, the Knudsen profiles farther out along line NB9 (Fig. 7) suggest that the Agassiz Unconformity rises toward the lakebed in a landward direction, so that the thickness of Saskatchewan River deposits in this area may be quite thin. It is also possible that the sandy shoal and 'levee' represent former littoral and /or aeolian reworking of sand in the area at a time of lower lake levels in the mid-Holocene, prior to diversion of the Saskatchewan River. In this case, the channel might represent initial diversion of the river outlet behind a sandy barrier and dune complex, before the latter was overwhelmed and reworked by rising lake level.

Grab sample 317, collected close to the crest in a depth of 9.7 m, consisted of pebbly silty sand, oxidised at the surface, with a mean size of 116 μm. Sample 316, from 10.5 m water depth a little further lakeward, contained an olive grey clayey silt with a trace of fine sand and had a much finer mean size of 13 μm.

The core 201 site was 8 km east of CN2. In this area, the Seistec profile from line NB9 (reproduced with the data for core 201 in Appendix 10.4, this volume) shows ~5.4 m of Winnipeg Sequence sediment overlying the unconformity. The latter truncates the URI of Agassiz Sequence deposits. The Winnipeg sediments in the Seistec record contain a section of transparent or disrupted bedding between 0.5 and 1.7 m below the lakebed and occasional discontinuous lenses of transparent to disrupted stratification elsewhere, but generally show consistent parallel acoustic reflections.

The Knudsen 28 kHz profiles in the same area indicate lakeward thickening of the Winnipeg Sequence as the Agassiz Unconformity plunges gently downward in the same direction. Just east of core site 201, where a cross profile with higher gain shows detail within the Agassiz Sequence (Fig. 6B), conformable (draped) stratification in the latter is clearly truncated about 5.5 to 6.0 m below the lakebed in 13 m water depth. The profiles parallel to line NB9 (lines 171 and 173) were run mostly with lower gain and illustrate details within the Winnipeg Sequence (Fig. 7). The latter may pinch out at the base against the westward slope, but much of the sequence appears to continue upslope in a vertically contracting section. In the area of the core site (Fig. 6B), the Knudsen records show a less reflective interval in the upper 2 to 3 m of the section, with a more transparent unit 0.5 to 1.5 m below the lakebed, as in the Seistec record. The Winnipeg Sequence is more regularly stratified in the lower 2 to 3 m, but shows evidence of some discontinuities or disruption in the Knudsen profiles as well. Strong returns that occur sporadically through the upper half of the Winnipeg Sequence (Fig. 7) are of unknown origin, but may reflect coarse ice-rafted debris or compacted horizons resulting from ice scour.

Eastern shore of North Basin south of Marchand Point- 'yawl' line 196

A single, shore-normal, 28 kHz profile was obtained at this site (Fig. 1) before a forecast of deteriorating weather forced a return to *Namao*. No sidescan sonar or bottom samples were collected but a sample of sand was taken on the beach. In contrast to the high dunes at Spider Islands, further north along the same coast, the shore in this area consists of a low, narrow, transgressive barrier migrating landward across a broad wetland.

The nearshore profile (Fig. 8) is broadly consistent with the geology observed off Spider Islands. The narrow band of subaqueous beach sand pinches out in about 3.2 m water depth, at the base of a concave-up nearshore profile. From this point lakeward, the bottom is rough and erosional. It truncates Agassiz Sequence deposits exposed at the lakebed, except where interrupted by Precambrian outcrop. The profile continues to 1.35 km from the beach in 7.2 m of water, without encountering Winnipeg Sequence mud cover.

George Island- start of *Namao* line NB18, 'yawl' lines 160 and 168

George Island is an emergent part of the George Island Moraine (Todd et al., 1998) and consists of glaciofluvial sands and gravels rising up to 20 m above the lake, with paleocurrent directions toward the southwest. Large boulders are present along the southern shore (Dowling, 1900). During the present survey, the sidescan sonar fish, deployed from the yawl <2 m below the lake surface, struck a boulder in 6 m water depth a short distance off the south shore of the island. Sandy beaches are present in several embayments at the east end of the island and along the western shore, where dunes up to 15 m high have developed behind the beach.

A Seistec profile was obtained along line NB18, beginning in the harbour and running directly south off the margin of the George Island Moraine into the Berens Basin of northern Lake Winnipeg (Brunskill and Graham, 1979; Fig. 2 in Todd et al., this volume). At the start of the line (Fig. 9), the profile crosses a shallow sill about 4 m deep in the harbour entrance. Outside this sill the lakebed drops away rapidly to the top of a short linear slope from about 9 to 12 m water depth. This may be a wave-worked sandy apron at the base of the morainal outcrop. At the base of this linear segment, the lakebed slope is substantially reduced. A thin veneer of Winnipeg Sequence mud, ranging from about 0.3 to 1.1 m in thickness, drapes the erosional unconformity (AU) truncating Agassiz Sequence deposits. This unconformity is almost planar where the lakebed is >14 m deep, but is more irregular above that. A shallow moat is present close the base of the morainal slope, where the Seistec profile shows evidence of possible shallow slope failure, perhaps related to harbour dredging and dumping activity. Acoustic basement ranges from 25 to at least 47 m below the present lake level. The Seistec record shows no clear evidence of the morainal unit in the subbottom. This is not surprising, given the steep southwestern slope of the moraine recorded on a sleevegun profile obtained in 1994 (Fig. 19 of Todd et al., 1998). A linear extrapolation of the steep morainal slope off the harbour entrance (Fig. 9) would place the moraine surface beyond the limit of penetration (below the first multiple at the base of the linear apron in 12 m water depth).

Several nearshore profiles and associated Knudsen 28 kHz survey lines were obtained in the vicinity of George Island. The track plot (Map 1-6 in Appendix 10.1, this volume) shows one line extending south from the harbour (overlapping *Namao* line NB18 described above), two shore-normal lines in the southeast-facing embayment west of the harbour, two shore-normal lines running southeast and southwest from the southern headland, a shore-parallel line off the southwestern shore, and two 3 km long shore-normal lines on the north side of the island, running out from the two north-side beaches at the east end.

A shore-normal Knudsen profile (line 160) was run from 14 m water depth in to <2 m depth off the southeast-facing beach just west of the harbour (Fig. 10). This profile shows draped subbottom reflections near the start of line, where the penetration depth of the sounder was about 3 m, consistent with Agassiz Sequence sediments at or near the lakebed. The profile is linear to slightly mounded from about 13.2 m in to the base of the nearshore slope at 11.8 m. There is about 1 m subbottom penetration in this area to a very indistinct reflection surface. The bottom morphology suggests accumulation either of material moving down the profile under wave action, or possibly of spoil from harbour dredging. Grab sample 313, from 13.3 m water depth near the base of this unit, consisted of soft, grey, sand-rich mud, with a mean size of 7.3 µm (44% sand, 14% silt, 43% clay) and a 10 mm brown layer at the surface, interpreted as an oxidation horizon. This sample demonstrates the presence of at least 10 cm of soft sandy mud overlying the Agassiz sediments in this area and provides a measure of the minimum mud accumulation depth in this part of the lake. Above the base of slope at 11.8 m, the profile runs up to a double nearshore bar complex with bar crests in 3.0 and 2.6 m water depth and troughs at about 3.8 and 2.8 m. A subbottom reflection roughly 0.6 m below each bar crest and 0.4 m beneath the nearshore bottom landward of the inner bar may indicate the thickness of mobile sand on the inner part of the profile. Grab sample 310 from the inner bar crest and sample 311 from about 5.1 m water depth on the outer face of the outer bar contained well sorted, fine-medium, pale brown sand with mean grain size of 218 and 189 µm respectively (Appendix 10.7, this volume). Another grab at station 312 in 9.0 m depth produced only a trace of very fine sand in four attempts, but no sample was retained. This is consistent with a wave-packed sandy slope and the smooth, reflective, lakebed surface in the Knudsen profile.

The beach at the east end of George Island is part of a double tombolo structure. On the opposing north-facing beach, a nearshore profile was obtained along Knudsen line 168 (Fig. 11). The beach has a poorly developed nearshore bar in 1.6 m water depth, more akin to a terrace, with an almost linear outer slope extending to the base of sand at 3.8 m. The profile crosses a shallow basin north of the beach, bounded on the lakeward side by a rough shoal or ridge interpreted as a coarse gravel lag over morainal material. The inner basin appears to contain Agassiz Sequence sediments with a rough, erosional, lakebed surface. On the outer side of the ridge, the rough and highly reflective lakebed surface extends to the north in a broadly linear slope to about 10 m depth, where the bottom flattens out and the surface roughness begins to diminish progressively lakeward. The limit of Agassiz Sequence outcrop in this area is unclear, but the record suggests a thin cover of Winnipeg Sequence mud overlying Agassiz sediments at least 12 m thick in 14 m water depth near the outer end of the line.

Berens Island shoreface and lakebed to north- east end of *Namao* line NB17, 'yawl' lines 139 to 158

The east-west line NB17 approached within 8 km of the north shore of Berens Island at its east end. Sidescan sonar imagery collected along this line in about 15 to 16 m water depth (Fig. 12) revealed an irregular, blocky, and hummocky surface with highly varying reflectivity, similar to the erosional surface observed in the nearshore off nearby Berens Island, as well as at Willow Point in the South Basin and other sites throughout the lake. Patches and ribbons of large-scale wave ripples were scattered across the lakebed in this area, oriented toward the north and north-northwest, the direction of maximum fetch in this part of the lake. The wavelengths ranged from 1 m or less (the resolution of the sidescan records) to a maximum of about 1.5 m. By analogy to similar large-scale ripples recorded on shallow marine shelves (e.g. Forbes and Boyd, 1987), we surmise that these are scaled to the orbital diameter of the wave motions that generated the bedforms. Near the east end of the line, a thin veneer of Winnipeg Sequence mud was encountered in slightly deeper water (~16 m). This was interrupted by patches of mobile ripples standing slightly proud of the mud surface. Two grab samples were collected by *Namao* in this area. Sample 210 contained soft mud and sample 211 consisted of sandy pea gravel, consistent with sorting in wave-formed ripples. The mud is interpreted as a partial cover of Winnipeg Sequence silty clay accumulating over the former erosional shoreface surface, which is in the process of being abandoned as lake levels rise toward the south end of the North Basin.

Along the broad arcuate beach forming the north shore of Berens Island, 28 kHz nearshore profiles (Fig. 13) show a rough and irregular lakebed. The sidescan sonar imagery is similar to that observed offshore 8 km to the north (Fig. 12). The lakebed is an erosional surface truncating Agassiz Sequence deposits. Conformable bedding typical of the Agassiz Sequence is visible in some parts of the subbottom records. The local relief on the lakebed over distances of a few metres or less ranges from 0.1 m to 1.5 m or more. Based on detailed 1997 studies off Willow Point in the South Basin (to be reported elsewhere), we interpret this surface as the developing Agassiz Unconformity. This is scoured into the finely fractured, overconsolidated, silty clays by wave-induced turbulent boundary layer processes, coarse-sediment abrasion, and grounding lake ice. Grab sample 309, taken in 4.8 m water depth off Berens Island, contained angular mud clasts typical of the finely fractured AU shoreface at several locations in the lake.

A basal reflector underlying the Agassiz Sequence is present in most of the Knudsen profiles off Berens Island (Fig. 13). Because Ordovician carbonates are present on Barton Island at the west end of the beach (Map 1-5 in Appendix 10.1, this volume), where the barrier consists of pebble-, cobble-, and boulder-size slabs of limestone and dolomite, it is reasonable to suggest that this basal reflector in the nearshore is the eroded Ordovician rock surface. In places, especially toward the west end of the island, this surface is smooth and flat-lying to gently inclined. However, hummocky relief (up to 3 or 4 m) on this lower reflector in other areas of the Berens Island shoreface, and the dominance of crystalline rock fragments in fine gravel at the base of the beach midway along the north shore, suggest that the underlying material, at least in some areas, is a glacial ice-contact deposit derived from the northeast.

Preliminary reconstructions of basin tilting in the North Basin of Lake Winnipeg by Gaywood Matile (Todd et al., 1997) show southward retreat and breaching of an arcuate southeastern shoreline in the area north of Berens Island about 3 ka. We interpret the lakebed survey data presented above as evidence for at least 8 km of southward retreat of the shoreline and associated nearshore erosional platform.

Deer Island passage- Namao line SB15

In 1996, CCGS *Namao* ran line SB15 northward from the South Basin to the mouth of Washow Bay (Fig. 1). The line passed between Hecla Island and Black Island and then west of Deer Island, before crossing northeast toward the eastern shore of the lake and turning north toward Washow Bay.

Core 216 was taken in the narrows west of Deer Island (Fig. 3 in Todd et al., this volume), in an area where flat-lying Winnipeg Sequence sediments are truncated by the present lakebed (see Appendix 10.4, this volume). A prominent acoustic unconformity occurs 3.3 m below the lakebed. Two contacts are encountered in core 216, one at 3.42 m and the second at 2.04 m downcore. The uppermost unconformity in the Seistec record is at the present lakebed. The lower contact in the core is interpreted as the AU, underlain by stiff, crumbly, silty clay; its depth in the core is comparable to that estimated from the Seistec record.

This region of the lake is characterised by numerous unconformities overlying Agassiz Sequence deposits. About 8 km south of core 216, a complex set of deposits records several phases of cut and fill (Fig. 14). A channel or shallow basin in the AU is partially masked by gas. Another small channel or basin is present 600 to 700 m south (not illustrated). The extensive AU contact cutting underlying Agassiz Sequence deposits appears to form a cap on underlying gas and also cuts sediments infilling the small basin or channel. The AU and flat-lying Winnipeg Sequence deposits above it are cut by another unconformity just below the present lakebed at the left side of the figure. A broad mound, itself containing numerous truncations and a unit of relatively incoherent reflections, overlies a near-horizontal contact cutting the lower Winnipeg Sequence sediments. The incoherent unit may represent coarse sandy bedforms or may reflect ice scour disruption or ice-raft deposition. Ice scour is also suggested by the irregular morphology of the lakebed. The numerous unconformities and cross-cutting nature of the modern lakebed in this area attest to high current velocities in the narrow passages of the central lake. This is consistent with evidence for energetic wind-generated currents in The Narrows at the south end of the North Basin (Kenney, 1979; Todd et al., 1998).

Hecla-Black Sill- *Namao* line SB15

Core 96900-217 was collected along line SB15 on the sill between Hecla Island and Black Island (Fig. 1), where a small basin or channel similar to that described above disrupts the otherwise almost-flat Agassiz Unconformity. The AU lies at or near the lakebed in the vicinity of the core site (see core 217 description and associated Seistec record in Appendix 10.4, this volume). The channel-like feature is about 100 m wide and up to 4.8 m deep. Gas trapped below the basin or channel masks the Agassiz Sequence in that area only, good penetration being achieved to either side. The channel fill consists of irregular, steeply dipping reflections on the southern flank, passing into broadly concave, partially onlapping, stratified channel fill. The latter is truncated by a second basin- or channel-like unconformity, about 1.3 m below the present lakebed at its deepest point on the profile. The upper depression is filled by onlapping Winnipeg Sequence muds.

In core 217, soft, faintly laminated clay and silt-clay mud overlies a sharp contact at 1.32 m downcore. Firm, crumbly, mostly massive silty clay occurs between this contact and a second sharp contact at 3.02 m, underlain by stiff, grey, silty clay. Bulrush (*Scirpus* sp.) seeds just above and just below the upper contact were dated 3340 ± 50 years BP (CAMS-35498) and 3340 ± 40 years BP (CAMS-46190), respectively (Telka, this volume). *Chenopodium* sp. seeds with an AMS age of 3910 ± 60 years BP (CAMS-46191) were found, along with a large unidentified mollusc shell, deeper in the silty-clay unit between the two unconformities.

The combined acoustic and core stratigraphy leads to the following interpretation. If the depression in the lower unconformity is indeed a channel, it may have been cut by overflow from a lake in the present South Basin of Lake

Winnipeg, draining northward between the present islands. The steeply dipping reflections on the southern flank may be point-bar sands associated with a channel bend. Alternatively they may be part of a washover unit infilling the depression as the transgressive shoreline of a lake to the north migrated into the area. The latter interpretation is consistent with the core stratigraphy and radiocarbon age data. These demonstrate that the lower unconformity was cut prior to 4 ka and the upper contact is associated with a shoreline 11 to 12 m below present lake level, dated 3.3 ka.

Pearson Reef moraine and buried beaches- *Namao* line (core reconnaissance)

One of several Seistec profiles across the Pearson Reef moraine was reproduced as Fig. 17b of Todd et al. (1998). This showed lens-shaped units on either side of the moraine ridge where the latter projects above surrounding lakebed mud. These lenses are buried beneath 1 to 3 m or more of Winnipeg Sequence mud. They rest on morainal sediments and truncated Agassiz Sequence deposits close to the moraine ridge, but extend out over thin wedges of Winnipeg Sequence mud in some places. Their internal structure consists primarily of outward-dipping clinoform reflections, representing a process of lakeward progradation over time. Particularly on the west side of the moraine, the lenses take the form of a flat-topped or gently sloping terrace that drops off into deeper water. On the east side, they expand into a discrete ridge with a low basin on the inner side toward the moraine. The ridge crest lies in about 12 m present water depth and the terrace is generally a little deeper (13 to 14 m).

The ridge rests on a subhorizontal erosion platform about 150 m wide (Fig. 15), cutting across Agassiz Sequence sediments of the Middle Transparent Interval (in the South Basin seismostratigraphy of Todd et al., 1998). The platform lies about 14 m below present lake level. Lakeward of this platform, the AU steps down to a lower terrace sloping eastward from less than 16 m at the inner end to approximately 17 m present depth about 500 m further out in the lake. This part of the unconformity cuts across the upper Segmented Reflective Interval of the Agassiz Sequence. A thin wedge of very gently lakeward-dipping clinoforms rests on this lower erosional terrace. Irregular, somewhat discontinuous, higher-amplitude reflections are present in the Winnipeg Sequence above the lower wedge, extending upslope to a low mound at the base of the upper erosion platform and into a thin and gently lakeward-sloping wedge on the inner part of the upper platform. The upper ridge has an internal structure indicating upward and lakeward growth. The outermost clinoforms are more steeply dipping.

We interpret these features as a former beach and spit associated with lake levels initially 16 m or more below present mean water level, rising to 13 m and then less before final abandonment and burial. The lower AU terrace cutting the Segmented Reflective Interval from 17 up to <16 m below present lake level is interpreted as initial shoreline development associated with the earliest known deposits of proto-Lake Winnipeg in the South Basin. Core 96900-220, which intersected the thin clinoform wedge resting on this terrace, contained almost 1.5 m of sand at the base of the core. A pelecypod shell with an AMS age of 4760 ± 70 radiocarbon years BP (CAMS-32193), among the earliest post-Agassiz dates in the South Basin, occurred near the base of the core in the lowermost part of the sand deposit resting on the terrace. Accounting for a hardwater reservoir error of 255 years for shells in Lake Winnipeg (Lewis et al., this volume), this indicates that an aqueous environment existed at this site approximately 4.5 ka. A few centimetres higher in the core, *Chenopodium* sp. (goosefoot) seeds with an AMS age of 3920 ± 70 years BP (CAMS-35495) suggest initial shoreline development approximately 16 m below present lake level circa 4.0 ka (Telka, this volume). By comparison with other cores intersecting the AU, abundant organics in the lower 3 cm of the core are consistent with an interpretation that the core may have terminated at the unconformity. Two beds of graded fine-pebble gravel within the sand unit are consistent with an interpreted early beach represented by the thin lakeward dipping reflections in the lower wedge at 15 to 16 m below present lake level.

Following this initial phase, the lake is believed to have risen rapidly to approximately 14 m below present, forming the upper erosional platform and capping inner beach wedge. With a further rise in lake level, the low mound at the outer end of the upper platform may have developed as a small swash bar or as a nearshore bar associated with the early phase of spit growth a little later. Lakeward transport of shoreline material during storms may have formed the crudely stratified sandy and silty inclusions in the lower mud of core 220 as lake level rose further to about 13 m, where it may have stabilised for a time. This was the level at which the spit developed, forming a barrier beach enclosing a shallow backshore lagoon.

The north-south trending morainal ridge must have formed a headland protruding southward into the rising South Basin precursor of Lake Winnipeg (cf. Fig. 18 of Todd et al., 1998). This headland would have been subjected to increasing wave erosion as lake levels rose, trimming the unconformity across flanking Agassiz Sequence deposits and forming an erosional platform and cliffs at the southern point. On the more protected western side of the headland, with shorter fetch and less energetic waves, a narrow beach and nearshore terrace developed. On the more exposed eastern side, beach development may have been augmented by longshore transport away from the headland, leading to development of the northward-growing spit or barrier beach and associated backshore lagoon. Cores 218 and 219 obtained a short distance alongshore to the south of Fig. 15 (see core descriptions in Appendix 10.4), contained lithologies consistent with the foregoing interpretation. Organics spanning an age range from 2940 ± 80 years BP (CAMS-35500) for raspberry seeds to 1970 ± 170 years BP (CAMS-35494) for terrestrial beetles were recovered from lagoonal deposits behind the spit (Telka, this volume).

A final phase of abandonment and overstepping is inferred from the flat-topped morphology of the spit in the area of Fig. 15, suggesting wave trimming as lake level overtopped the spit, with deposition of a narrow wedge of sand at angle of repose on the lakeward flank. This continued for a time as mud began accumulating at the foot of the ridge, as suggested by minor interfingering at the toe. At this stage, the longshore sediment supply was probably interrupted, leading to more rapid abandonment and overstepping. The lack of an erosional terrace above and landward of the former spit may reflect in part the dissipation of wave energy on what had become effectively a nearshore bar. Eventually the water depth increased to the point where mud deposition could occur on top of the ridge and the former shore-zone sands were buried under basin muds of the present Lake Winnipeg South Basin.

Embayment on southwest side of Elk Island and lakebed to west- 'yawl' lines 119 to 131

A triangular network of 28 kHz profile and sidescan sonar survey lines was run in the embayment off the southwest end of Elk Island (Fig. 1) and the breached tombolo running south to the mainland shore. In some areas, a rough, irregular, erosion surface cutting across Agassiz Sequence deposits is exposed at the lakebed (Fig. 16). Elsewhere, the Agassiz Unconformity is buried by a variable thickness of Winnipeg Sequence mud and sand. Coring from the lake ice in March 1997 (reported elsewhere) also demonstrated the presence of peat at shallow depth below the lakefloor in 4.4 m water depth in this area (see Telka, this volume).

Knudsen sounder profiles and sidescan sonar imagery collected off the western shore of Elk Island (' yawl' line 130 and outer end of line 129), show almost ubiquitous, cross-cutting, narrow- to wide-keeled ice-scour morphology on the lakebed (Fig. 17). The predominant orientation of the scours is south to east-southeast. These scours, cut into soft Winnipeg Sequence clay, range from sharply defined cuts to fainter, degraded features. In places, the 28 kHz profiles show a thin veneer of Winnipeg Sequence mud overlying the degraded scours. This is consistent with observations north of Elk Island, using the dual-frequency sidescan sonar on CCGS *Namao*, where less sharply defined scours seen on the 110 kHz sidescan were invisible on the higher-frequency 330 kHz records.

Willow Point- 'yawl' lines 111 to 118

Detailed surveys were undertaken by the yawl in nearshore waters off Gimli (Fig. 1) and along the shoreface north of Willow Point, as well as north of Gimli at site 31 of Penner and Swedlo (1974). In 1997, these were supplemented by more detailed surveys, diver observations, and other data reported elsewhere. Here we present a brief description of the erosional shoreface surface off the northeast-facing beach at Willow Point, for comparison with data from Spider Islands, Berens Island, Sans Souci, and other sites.

Willow Point is a boulder-strewn hardpoint interpreted as a topographic high on the underlying glacial till surface (Dowling, 1900; Forbes and Frobel, 1996). This was confirmed by sidescan sonar imagery in 1996 and Seistec profiling in 1997. Tombolo-like barriers extend from the point southwest and northwest (the latter northeast-facing beach connecting to Gimli), enclosing a large lagoon and marsh complex. The beaches consist of fine-medium sand with some coarse sand and fine gravel. They have a relatively small cross-section and are capped locally by minor dunes. Beach sand extends only a short distance into the lake, to depths of no more than 2 m. In depths of 2 to 5 m, approximately, the shoreface lakebed is a rough erosional surface truncating consolidated silty clays of the Agassiz Sequence (Fig. 18), which show steeply dipping reflections. This is the developing Agassiz Unconformity (AU). Also evident are numerous pits or trenches, some or all of which are products of ice scour. These impart a local relief of almost 1 m to the irregular surface, which is also characterised by low mounds. Grab samples collected from the bottom in 1996 and cores and diver samples in 1997 reveal a surface composed of finely fractured stiff silty clay. Soft Winnipeg Sequence mud onlaps the unconformity in water deeper than about 5 m.

Sans Souci and Netley Marsh shoreface- 'yawl' lines 205 to 211 and *Namao* line SB1

The southern shore of Lake Winnipeg consists of a low, transgressive, sandy barrier migrating landward over wetland deposits of Netley Marsh (Nielsen and Conley, 1990; Forbes and Frobel, 1996; Todd et al., 1997). The rate of landward migration has been documented from airphotos by Penner and Swedlo (1974) and Nielsen and Conley (1990). However, little or no information has been available from the nearshore and shoreface.

In 1996, the ' yawl' ran a pattern of Knudsen 28 kHz and sidescan sonar lines in the area of Sans Souci and Chalet Beach, in the southwest corner of the lake, and a profile northward from site 8208 (Fig. 15 of Forbes, this volume) just west of the Red River navigation channel (see Map 1-13 in Appendix 10.1, this volume). Data from the latter site showed little, perhaps because the bottom was consistently sandy, or because of gas in the subbottom, a common occurrence that rendered Seistec profiles from *Namao* mostly useless in the southern South Basin. However good subbottom imagery was obtained at Sans Souci (Fig. 19). As at Willow Point, this shows the very limited extent of beach deposits, although at this site there is a single nearshore bar. Lakeward of the bar, the bottom is again erosional, cutting across conformably stratified deposits of the Agassiz Sequence. As at other sites where the AU is forming across the shoreface, the bottom is rough with local relief of several decimetres or more. Further north on the profile, off Matlock, sidescan sonar shows dipping strata of Agassiz Sequence deposits truncated at the lakebed (Fig. 20). In the lower right corner of the figure, the feather edge of Lake Winnipeg basin mud can be seen covering the exposed Agassiz Unconformity.

At this time we have very limited data from the southern South Basin north of Netley Marsh. However, one small window through the widespread gas mask was obtained on *Namao* line SB1 in 1994, at the site later sampled in core 96900-224. This site in a depth of 8.5 m is 16 km north of the Netley Marsh shoreline. The Seistec profile (see Appendix 10.4) shows little clear structure, but a hint of more reflective material from 6 to 7 m below the lakebed. At greater depth, there is evidence of draped (conformably stratified) Agassiz Sequence material. The prominent reflective zone may therefore represent the AU, but appears to have some thickness. Core 224 contained 5.5 m of clay and silt-clay mud underlain by 0.32 m of mud with fine sand layers, wood fragments, and plant debris, underlain beneath a sharp contact by fine to medium sand with shells and shell fragments. A bivalve shell 7.1 m downcore in the sand gave an AMS age of 4090 ± 60 years BP (CAMS-35615), while *Helianthus* sp. and *Scirpus* sp. seeds at 5.8 m downcore yielded ages of 3550 ± 70 years BP (CAMS-35496) and 3570 ± 120 years BP (CAMS-35501), respectively (Telka, this volume). The core represents a transgressive fining-upward sequence, from beach or nearshore sand at the base, representing a shoreline 13-14 m below present at 3.5 to 4.0 ka, to mud with numerous storm layers of sand and organics, to mud with occasional thin silt lenses and laminae to massive or faintly laminated soft mud.

DISCUSSION and SUMMARY

Results presented here confirm the general applicability of the seismic stratigraphy developed by Todd and Lewis (1996) and Todd et al. (1998), as illustrated for the North Basin in Figure 3. This involves conformable glaciolacustrine deposits of the Agassiz Sequence draped over the underlying acoustic basement (bedrock or glacial ice-contact deposits) and truncated by a broad regional unconformity - the Agassiz Unconformity (AU). Overlying the AU are flat-lying deposits of the Winnipeg Sequence. Some variation in the internal stratigraphy of Agassiz Sequence deposits occurs between the North and South Basins of the lake (Todd et al., 1998). The results presented in this report point to other minor stratigraphic variations in the confined central-lake passages, over submerged relict shore and shoreface deposits, and in the nearshore. Glacial deposits are thin or absent at the base of the Quaternary section over much of the lake basin, except in morainal ridges mapped by Todd et al. (1998), although borehole data around the South Basin suggest thicker ice-contact deposits (Penner and Swedlo, 1974).

Lakebed sediments in the central narrows are characterized by additional unconformities just below and above the AU (Fig. 14). Large current-generated bedforms are also found just north of The Narrows, at the south end of the North Basin (Todd et al., 1998) and may be present in other narrow passages. Further stratigraphic complexity is encountered where relict shore deposits are preserved beneath the lakebed, including coarse sandy beach and nearshore facies as well as relict lagoon deposits (Fig. 15).

Winnipeg Sequence muds are restricted to water depths typically greater than about 6 m in the South Basin (Figs. 18 and 20) and 13 m in the North Basin (Figs. 4, 7, 9, 10), except in protected (restricted fetch) waters where modern mud deposition extends into shallower water. Above these limiting depths for stable mud accumulation, the lakebed typically constitutes a rough erosional surface cutting across the undulating structures of the Agassiz Sequence (e.g. Figs. 5, 8, 11, 13, 16, 18, 19, 20). In these situations, the modern lakebed represents the actively developing AU.

A smoothly eroded AU surface at the base of the shoreface off Spider Islands and thin Winnipeg Sequence mud in the vicinity of core 105, overlying a planar unconformity, are consistent with a mid-Holocene interval of lowered water levels, at least 8 m below the present mean lake level, which can be attributed in part to isostatic tilting but is also thought to have been enhanced by a more arid climate (Lewis et al., 1998).

Lakebed exposures of Agassiz Sequence deposits often have a thin patchy veneer of coarse sand and scattered gravel, which is reworked by waves to form large-scale ripples. Abrasion by moving sand and gravel may be an effective contributor to ongoing erosion on these surfaces. The extent to which ongoing erosion continues in depths of about 15 to 16 m on line NB17 is unclear. The discontinuous cover of mud at near-equivalent depths in the area suggests that the exposed erosion surface may be largely inactive but just at the limit for mud deposition. These deeper exposed surfaces, also encountered at core 109 to the northeast in about 15 m water depth (see Figure 3 of Todd et al., this volume; Map 2 on CD-ROM), are interpreted as former shoreface surfaces that were active when the shoreline lay further lakeward in this area. Ongoing transgression under rising lake levels in the southern North Basin has pushed the shoreline back to the present north shore of Berens Island (Fig. 13) and Disbrowe Point (Forbes, this volume).

A submerged channel extends at least 2.5 km into the lake off the Saskatchewan River outlet (Fig. 6). A broad levee-like mound or ridge of sand lies along the eastern side of this channel and a shoal of wave-worked sand is present to the east (lakeward), cresting in a water depth of about 9.7 m. A clear understanding of the origin of these shoals would require additional surveys to map out the surface morphology and internal structure. The other areas in which submerged channels have been documented are off Berens River (Forbes, this volume) and in the area of the Nelson River outlet off Warren Landing, where the maximum charted channel depth is 13.7 m (Canadian Hydrographic Service, 1988). The outlet channel can be followed downstream into Playgreen Lake, where thalweg depths range from less than 4 m to a maximum of 10.4 m north of Kettle Island and 12.2 m to the southeast (Fig. 2; Canadian Hydrographic Service, 1988).

Nearshore bars have been documented at a number of sites (Forbes and Frobel, 1996), including a single bar at Spider Islands (Fig. 5) and Sans Souci (Fig. 19) and a double-bar system on the southeast shore of George Island (Fig. 10). Bars are absent at other sites, such as Willow Point (Fig. 18). Relict shore deposits have been mapped and cored in about 14 m present water depth along the flanks of the Pearson Reef Moraine in the northern South Basin (Fig. 15) and at a site about 16 km north of the present southern shoreline at Netley Marsh.

Evidence for lakebed scour by winter ice is abundant in the nearshore, where some of the prominent depressions in the Agassiz erosion surface are attributed to ice. Depending on the rate of erosional downcutting, these surfaces may integrate ice scour over many years. Extensive scour in surface and near-surface sediments of the Winnipeg Sequence was also detected on a large number of *Namao* sidescan records in many parts of the lake (McKinnon et al., Appendix 10.11, this volume), including an area of extensive scour north of Elk Island. Similarly extensive scour was observed in 'yawl' sidescan records off the western shore of Elk Island (Fig. 17).

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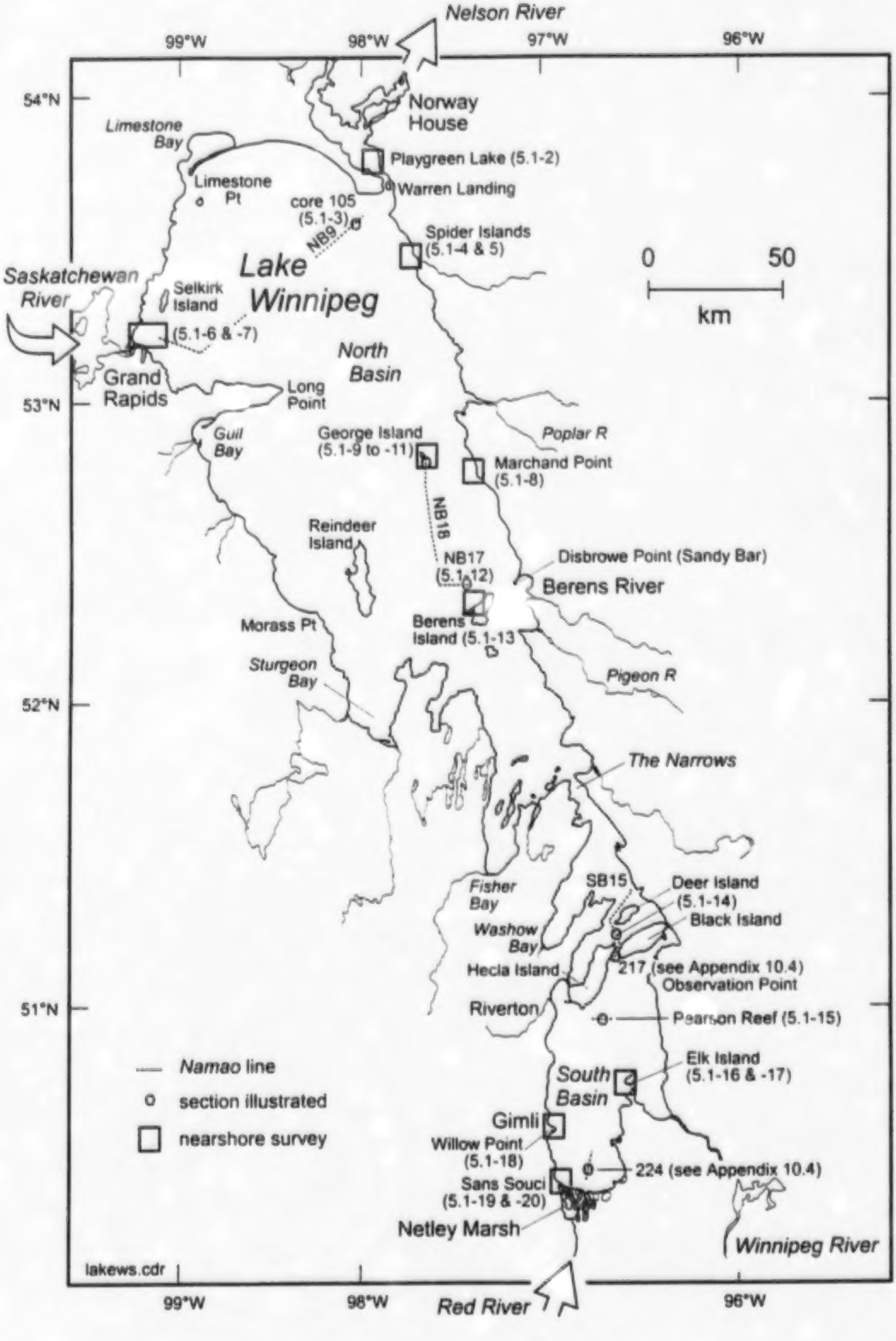
Nelson River
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
Norway House
Limestone Bay
Playgreen Lake (5.1-2)
Limestone Pt
Warren Landing
core 105 (5.1-3)
NB9
Spider Islands (5.1-4 & 5)
0
50
km
Saskatchewan River
Lake Winnipeg
Selkirk Island
(5.1-6 & -7)
Grand Rapids
North Basin
Long Point
Gull Bay
George Island (5.1-9 to -11)
Poplar R
Marchand Point (5.1-8)
NB18
Reindeer Island
NB17 (5.1-12)
Disbrowe Point (Sandy Bar)
Berens River
Morass Pt
Berens Island (5.1-13)
Sturgeon Bay
Pigeon R
The Narrows
Fisher Bay
SB15
Deer Island (5.1-14)
Black Island
Washow Bay
Hecla Island
217 (see Appendix 10.4)
Observation Point
Riverton
Pearson Reef (5.1-15)
Namao line
section illustrated
nearshore survey
South Basin
Elk Island (5.1-16 & -17)
Gimli
Willow Point (5.1-18)
224 (see Appendix 10.4)
Sans Souci (5.1-19 & -20)
Netley Marsh
Winnipeg River
lakews.cdr
Red River

Figure 1. Lake Winnipeg showing sites described in this report.

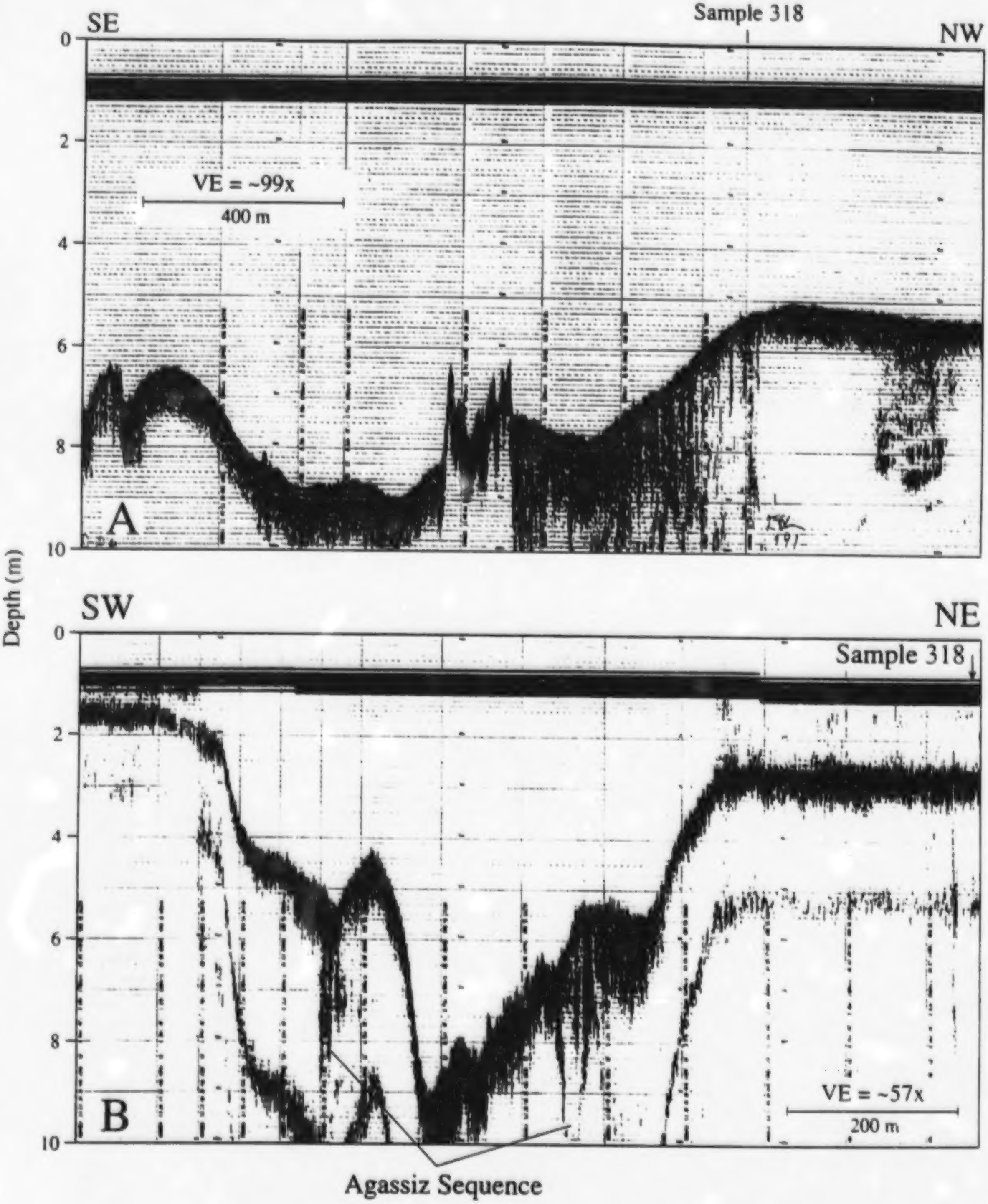

Figure 2. 28 kHz sounder profiles in Playgreen Lake (see Map 1 on CD-ROM and Map 1-9 in Appendix 10.1). (A) Part of line 191 run along axis of channel. (B) Part of line 194, crossing line 191 near its deepest point.

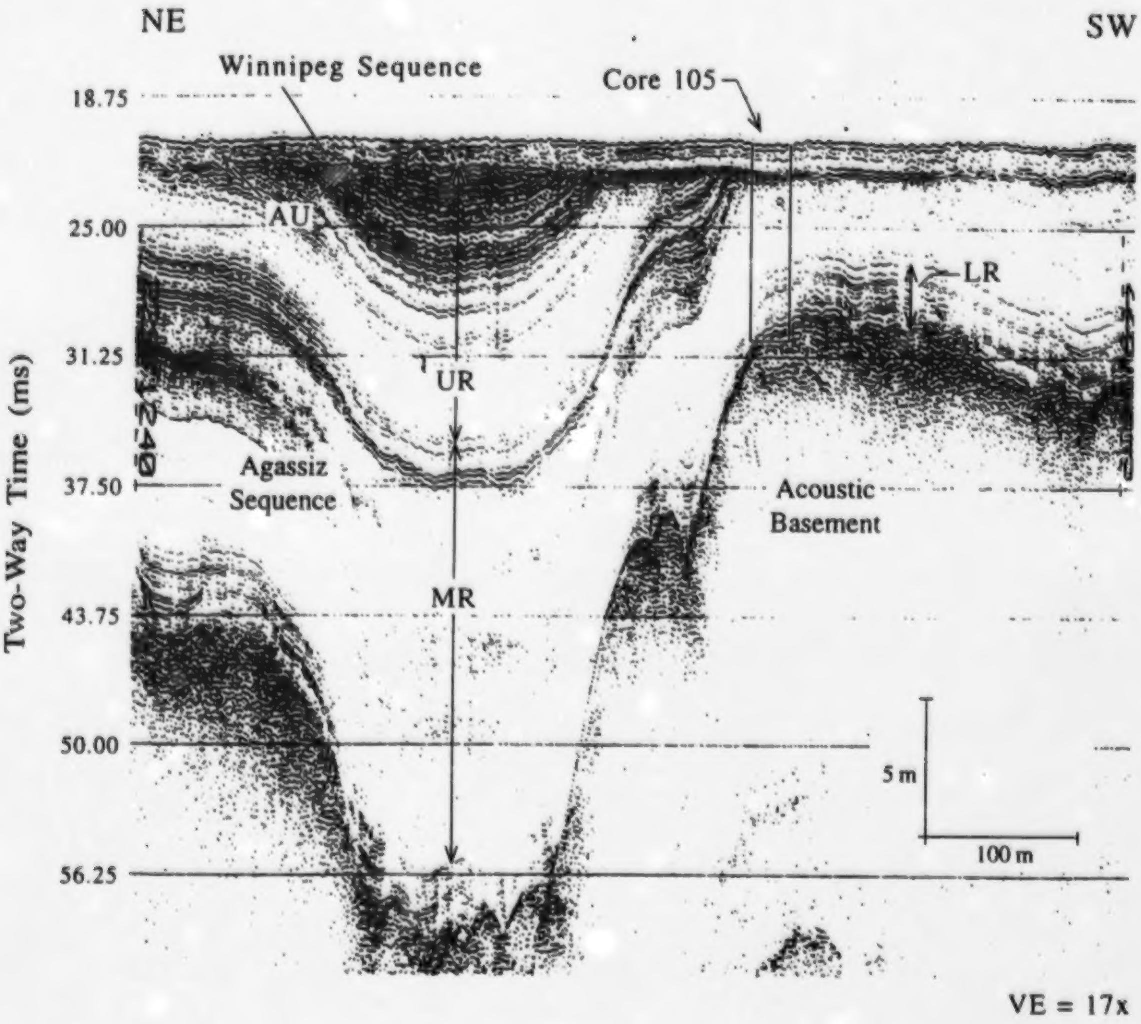

Figure 3. High-resolution seismic reflection (Seistec) profile near northeast end of line NB9 at site of core 105 in northeast North Basin (see Map 3 [inset] on CD-ROM), showing seismostratigraphic sequences. A thin unit of Winnipeg Sequence sediment overlies an unconformity truncating Agassiz Sequence deposits draped over acoustic basement. Acoustic subdivisions within the Agassiz Sequence are also labelled (after Todd and Lewis, 1996).

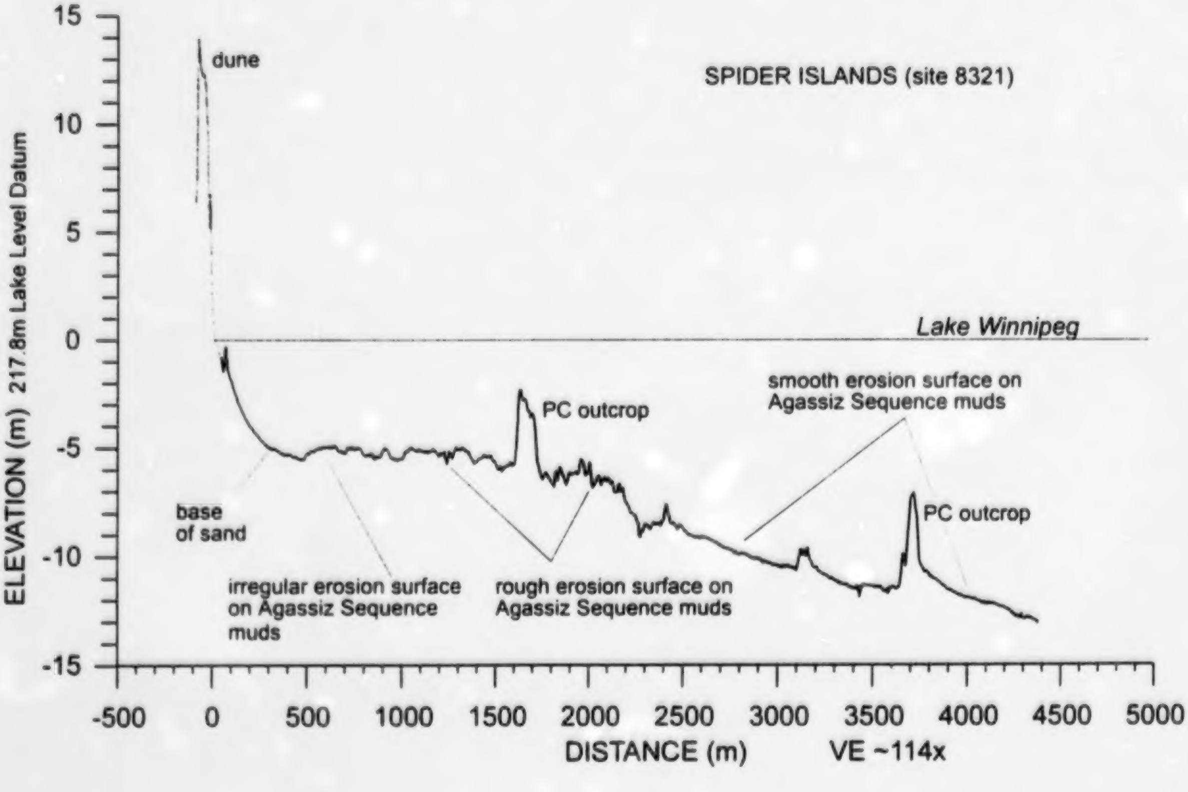

Figure 4. Composite topographic and bathymetric profile over parabolic dune and beach at Spider Islands, extending lakeward across the shoreface and into the North Basin to a depth of 13 m on 'yawl' line 195 (see Maps 1 and 1-10 in Appendix 10.1). Stippled box shows location of Fig. 5. A portion of the nearshore profile is illustrated in Forbes (this volume).

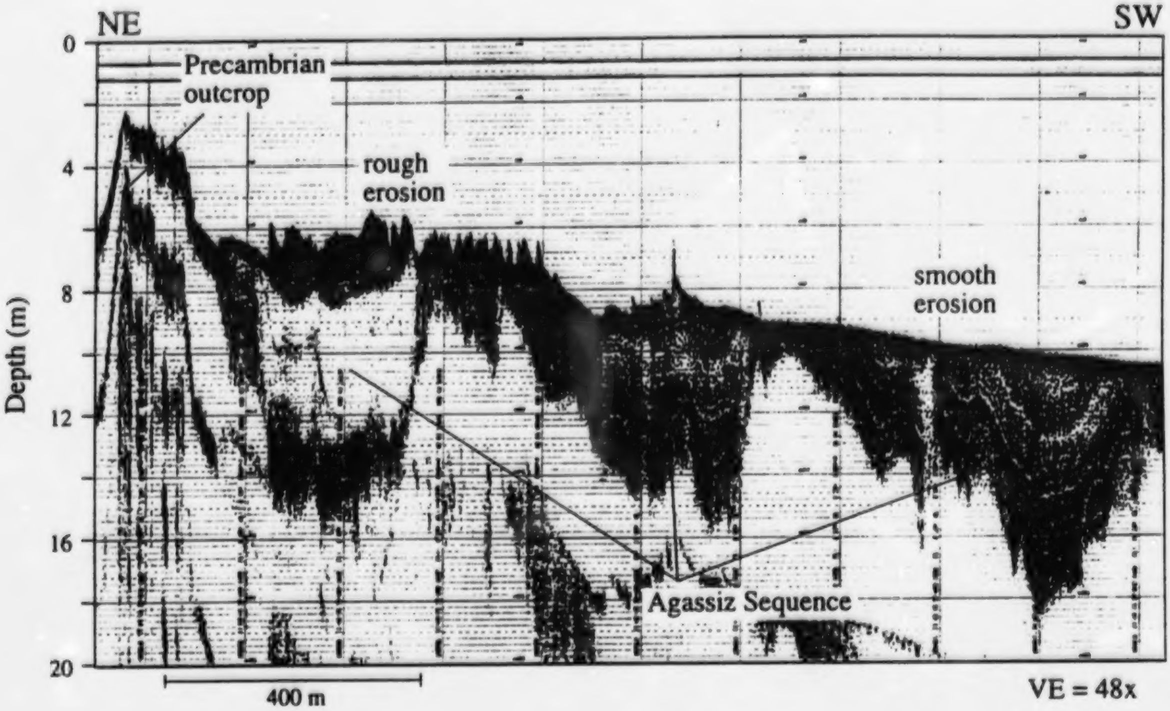

Figure 5. 28 kHz sounder profile (line 195) across lower shoreface off Spider Islands (see Fig. 4 and Map 1-10 in Appendix 10.1). Note the contrast in lakebed roughness between the smooth offshore part of the profile and the rough erosional surface above 8 m water depth.

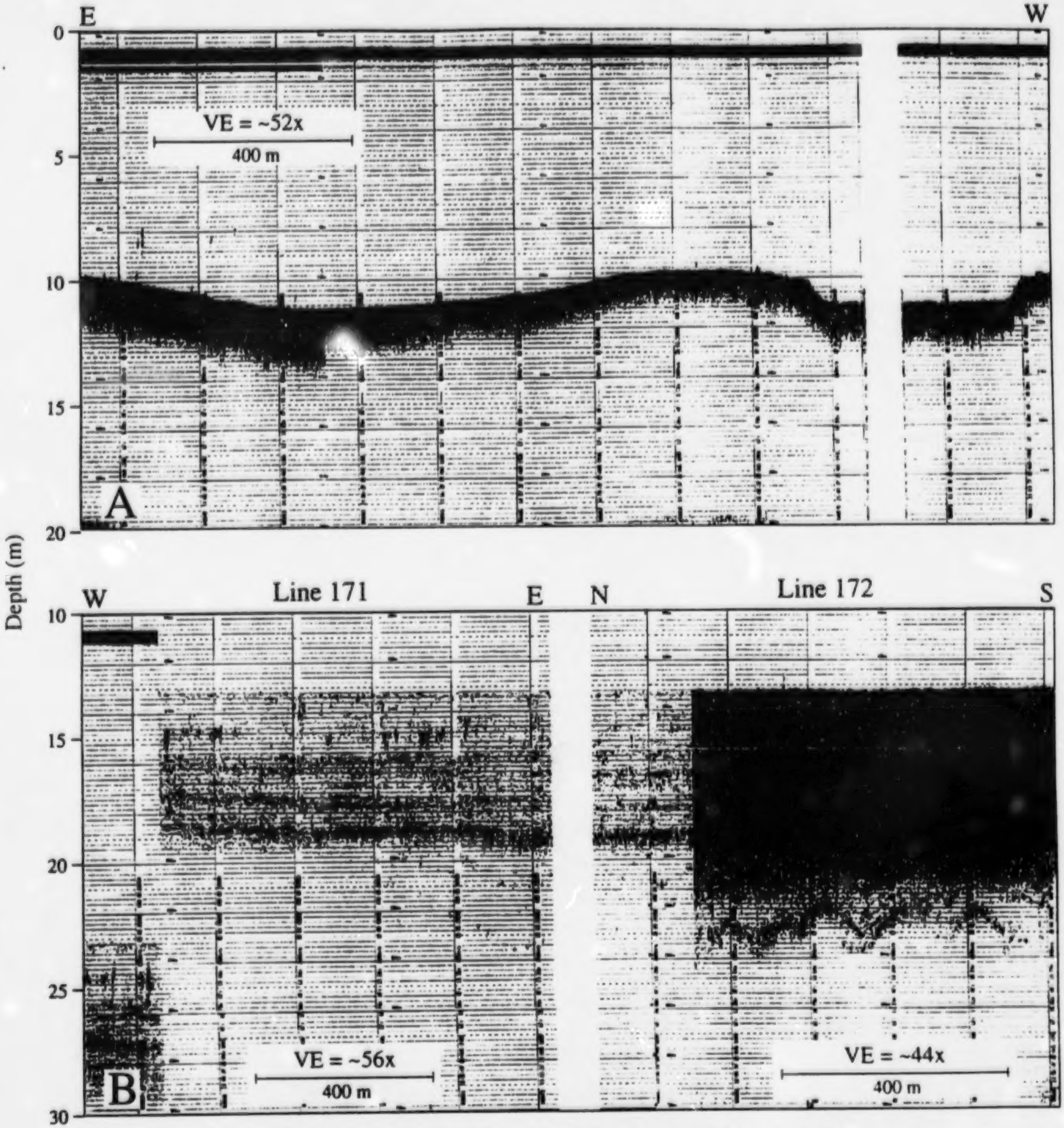

Figure 6. 28 kHz sounder profiles off Saskatchewan River outlet near Grand Rapids, western North Basin (see Map 1 on CD-ROM and Map 1-7 in Appendix 10.1). (A) End of line 173, with 180° change of course at outer end of Saskatchewan River channel near channel marker CN2. (B) Subbottom profile at end of line 171 and along short cross-track (line 172) normal to line NB9 near site of core 201. Gain increased to penetrate Agassiz Sequence deposits below unconformity.

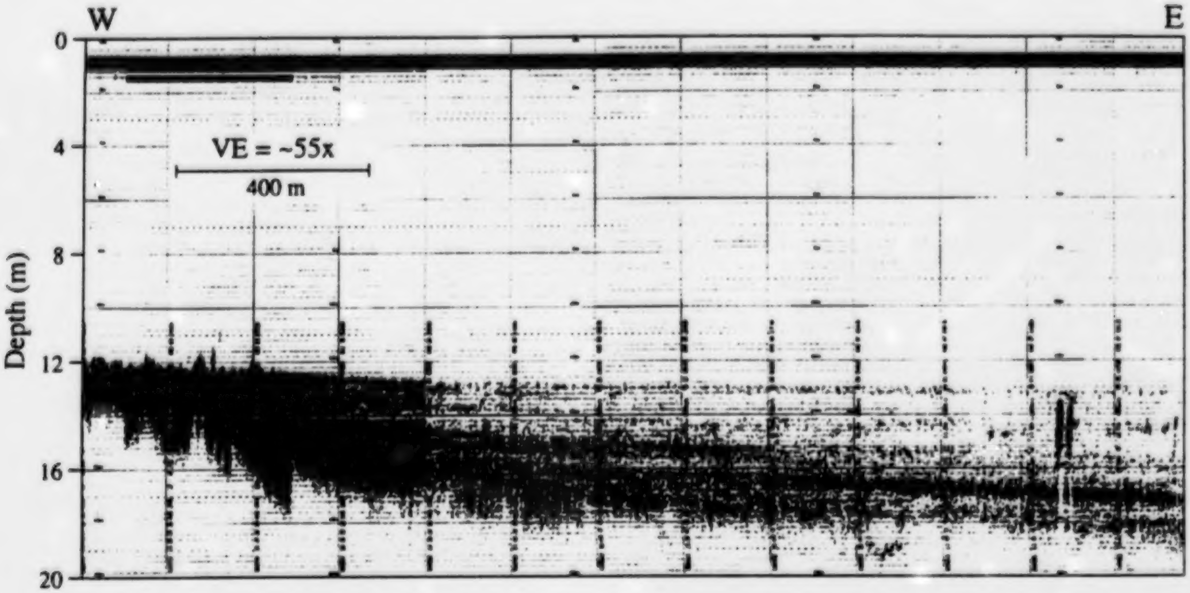

Figure 7. 28 kHz sounder profile (line 171) parallel to west end of line NB9 near site of core 201 off Saskatchewan River outlet, North Basin (see Map 1 on CD-ROM and Map 1-7 in Appendix 10.1). Surficial deposits of Winnipeg Sequence thicken lakeward to >5 m near the core site, consistent with the thickness observed in the Seistec record (Appendix 10.4). Expanded scale of 28 kHz record shows detailed stratigraphy and two-part division in the Lake Winnipeg sediments (see text).

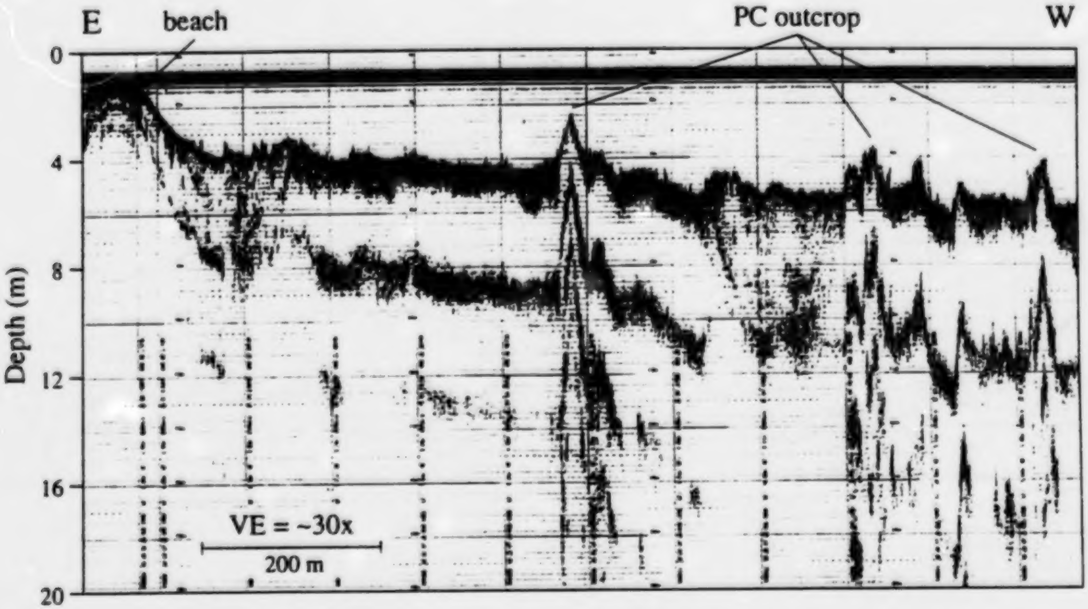

Figure 8. 28 kHz sounder profile (line 196) running out from beach south of Marchand Point, eastern shore of North Basin (see Map 1 on CD-ROM and Map 1-11 in Appendix 10.1). Small fringing barrier beach is fronted by narrow nearshore sand terminating in 3.2 m water depth. Erosional lakebed surface truncating draped Agassiz Sequence deposits is interrupted in places by Precambrian outcrop emerging above the surrounding lakefloor.

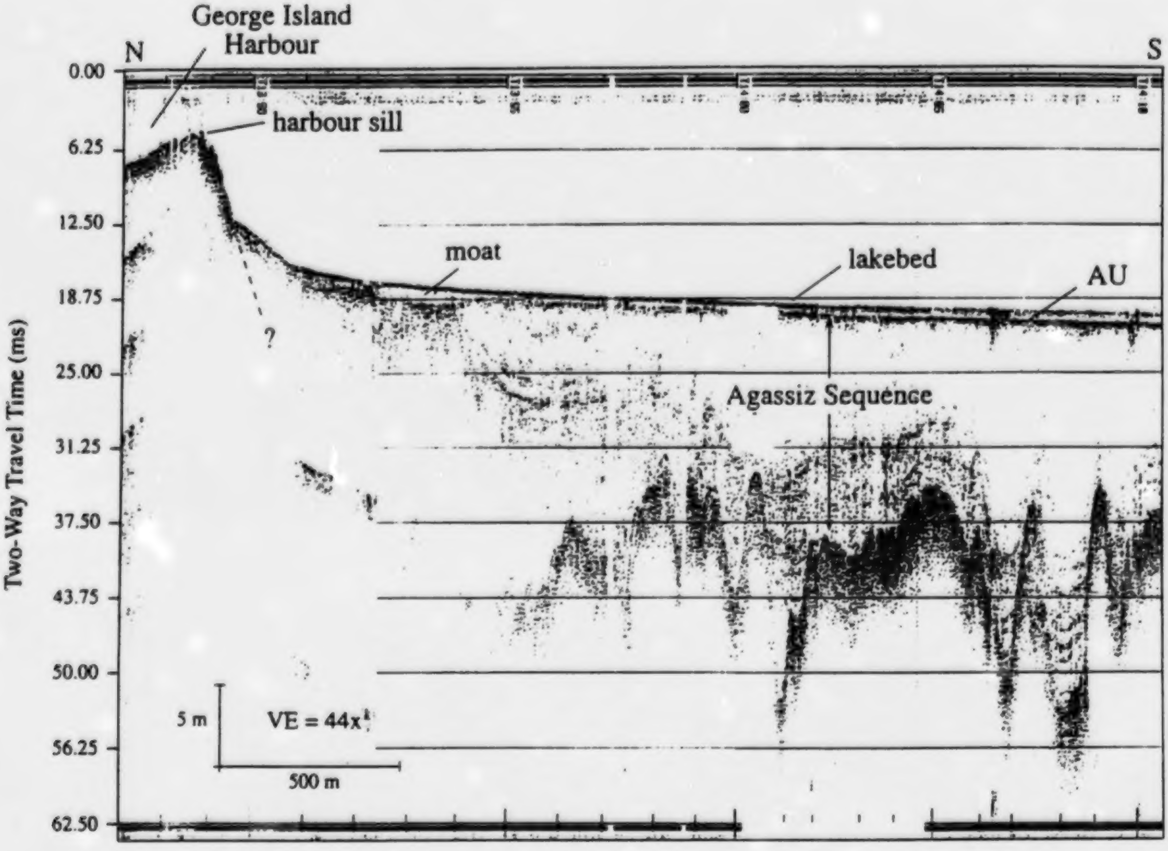

Figure 9. High-resolution seismic reflection (Seistec) profile running south from the harbour at George Island, at start of line NB18 (see Map 1 on CD-ROM and Map 1-6 in Appendix 10.1). Ice-contact deposits of the George Island Moraine at the harbour mouth drop away steeply (broken line) to below the limit of acoustic penetration in deeper water, where conformably stratified Agassiz Sequence deposits are truncated at the contact with overlying Winnipeg Sequence muds.

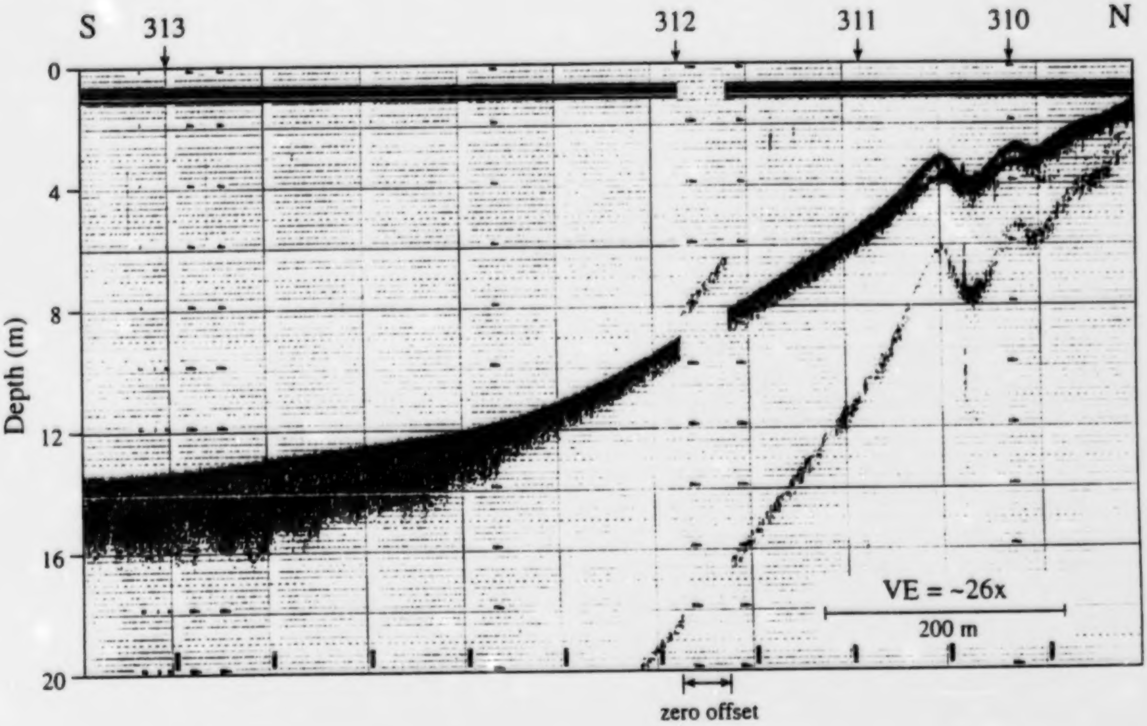

Figure 10. 28 kHz sounder profile running in toward beach (line 160) on south side of George Island west of the harbour (see Map 1 on CD-ROM and Map 1-6 in Appendix 10.1). Note thin mud cover over Agassiz Sequence deposits at the deep end of the profile, wave-packed sand on the lower shoreface, and two sand bars in the nearshore.

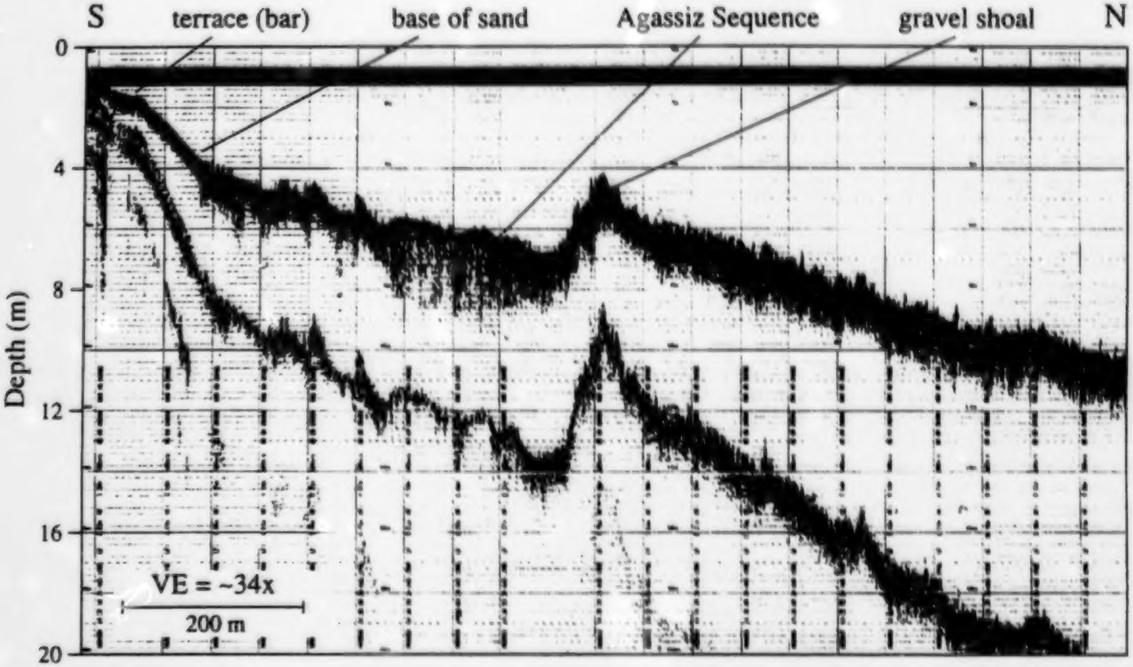

Figure 11. 28 kHz sounder profile (line 168) across nearshore basin on north side of George Island (see Map 1 on CD-ROM and Map 1-6 in Appendix 10.1). Thin deposit of Agassiz Sequence sediments, confined landward of a morainal ridge, is exposed and eroding at the present nearshore lakebed.

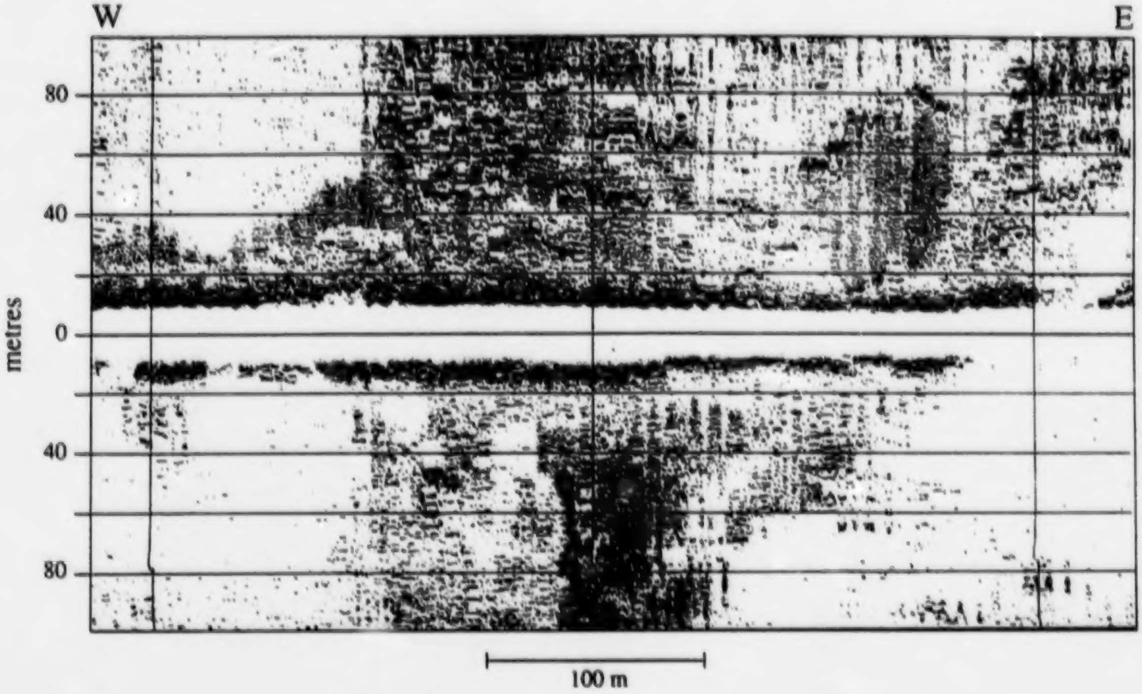

Figure 12. Simrad 330 kHz sidescan sonar image collected on line NB17, about 8 km north of Berens Island (see Map 3 on CD-ROM), showing erosional surface on Agassiz Sequence sediments exposed at the lakebed, similar to present nearshore surfaces observed at Berens Island and other sites.

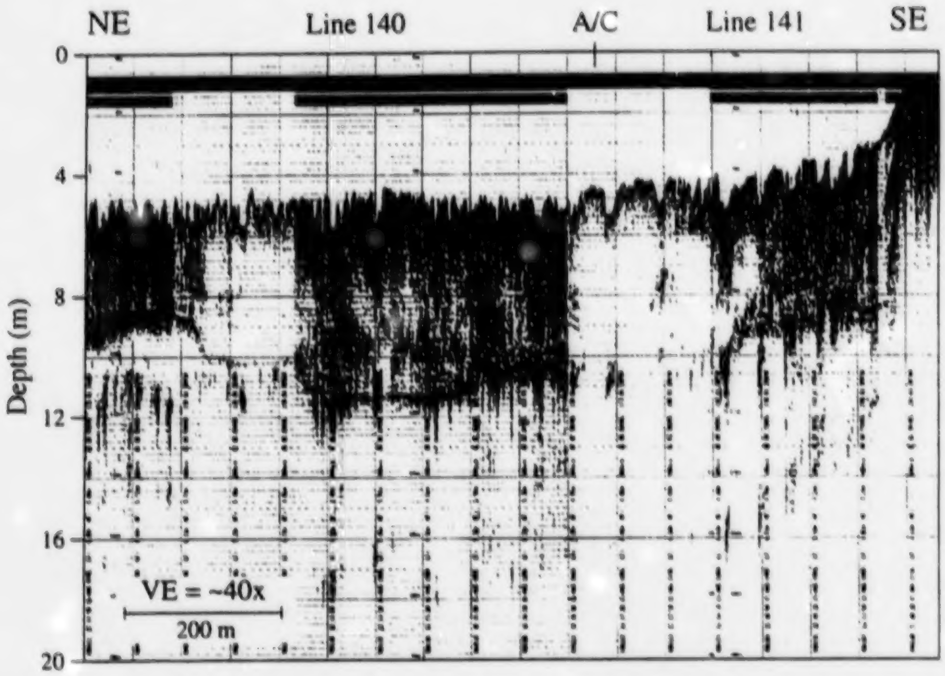

Figure 13. 28 kHz sounder profile (end of line 140 and line 141) off north shore of Berens Island (see Map 1 on CD-ROM and Map 1-5 in Appendix 10.1), showing rough erosional surface developed on Agassiz Sequence sediments exposed in the nearshore.

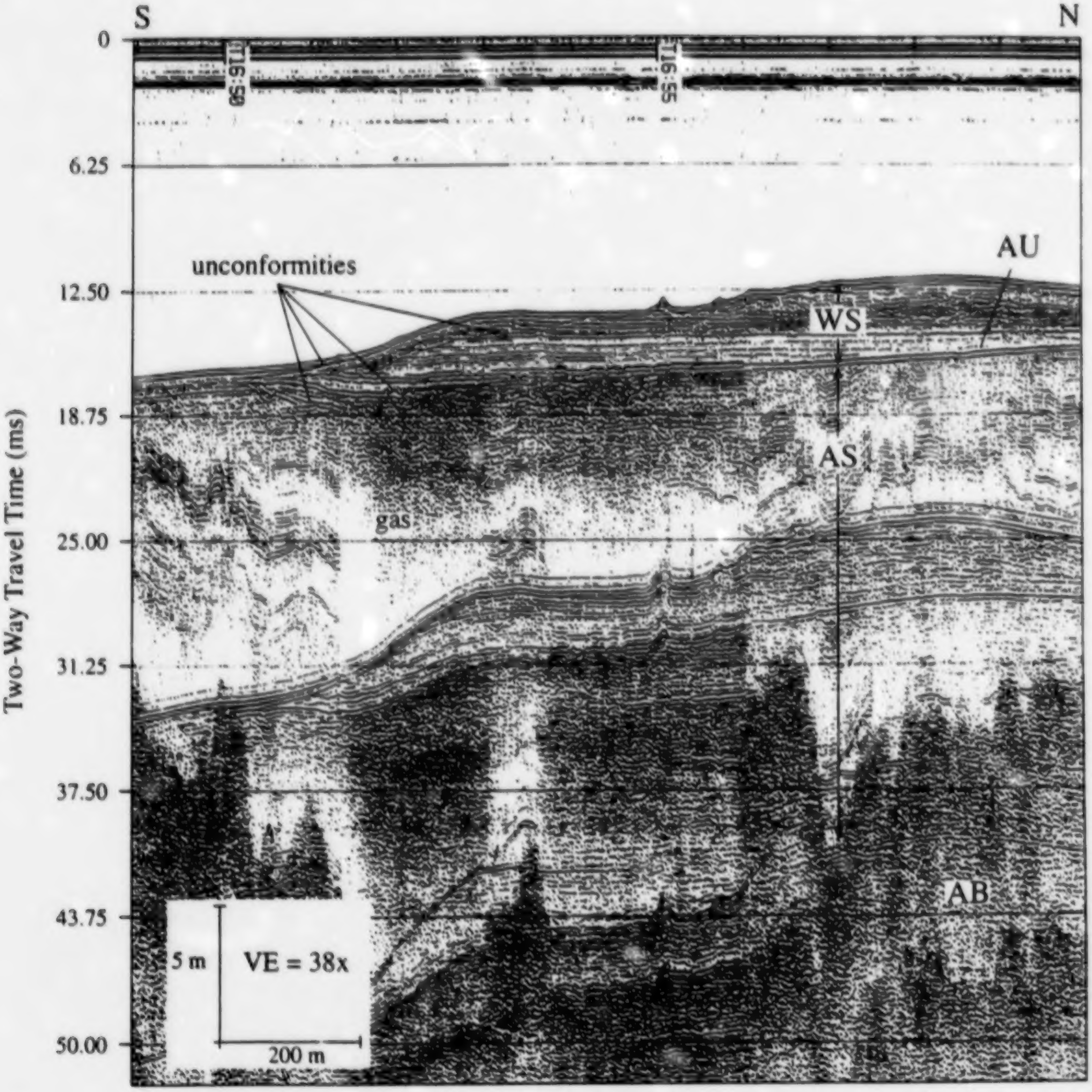

Figure 14. High-resolution seismic reflection (Seistec) profile on line SB15, about 8 km south of core site 216 (see Map 2 on CD-ROM). Profile shows complex suite of deposits and unconformities indicating several phases of cut and fill in this narrow section of the lake.

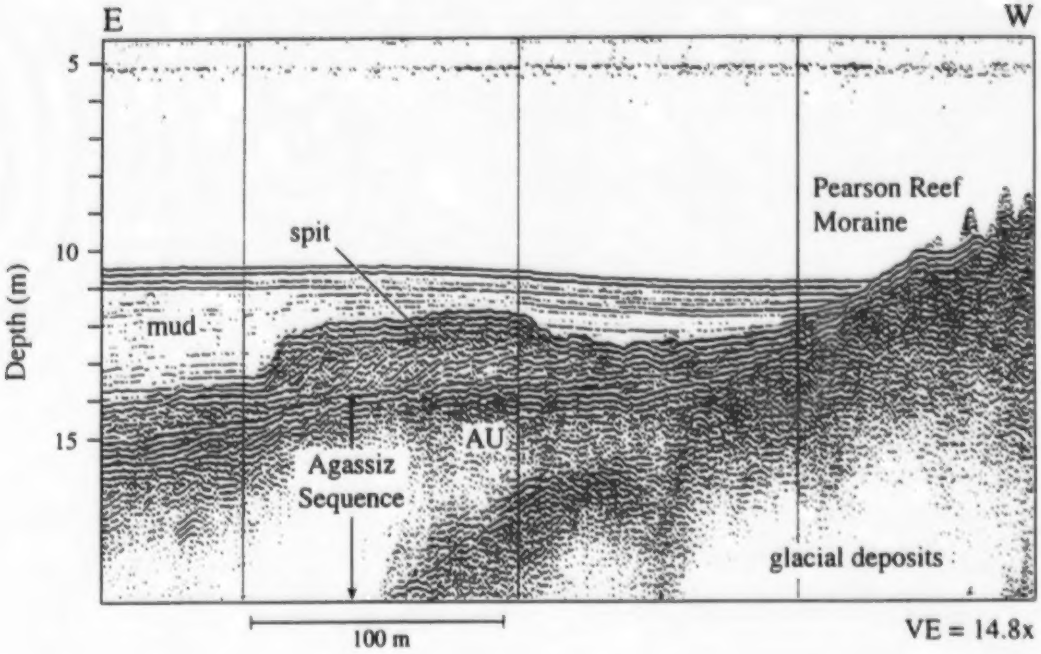

Figure 15. High-resolution seismic reflection (Seistec) profile over buried spit and associated shore-zone deposits on east side of Pearson Reef Moraine (see Map 2 [inset] on CD-ROM). Spit complex overlies unconformity at top of Agassiz Sequence, which in turn rests on ice-contact deposits along side of moraine.

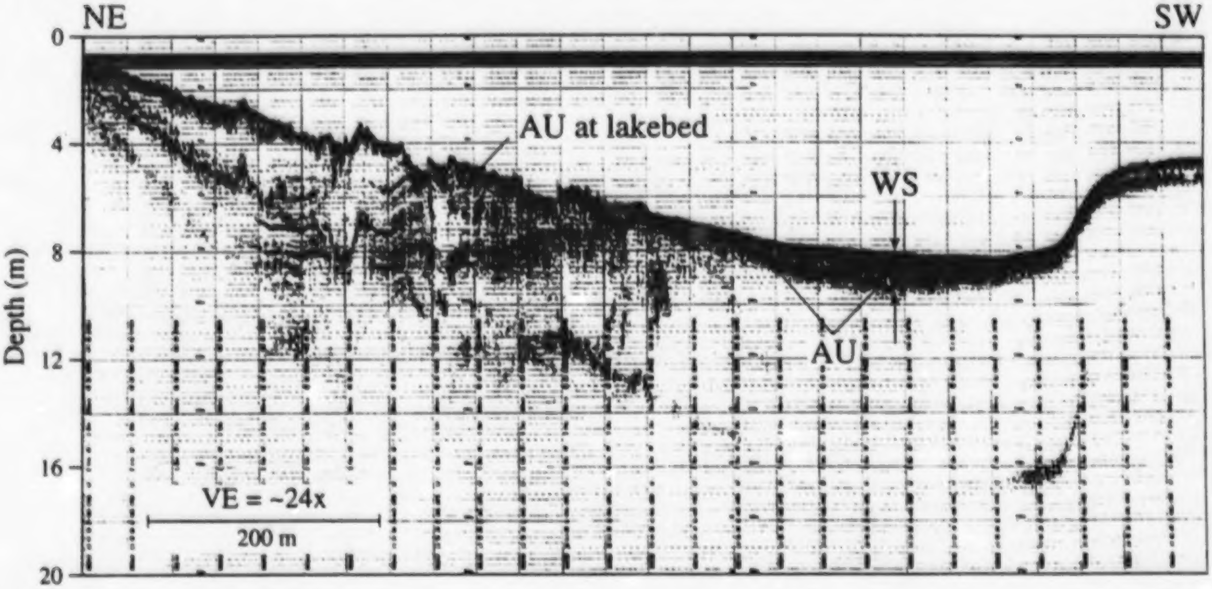

Figure 16. 28 kHz sounder profile (part of line 129) off southwest shore of Elk Island (see Map 1 on CD-ROM and Map 1-2 in Appendix 10.1), showing rough and smooth lakebed, erosional surface (developing Agassiz Unconformity) cutting Agassiz Sequence sediments, and variable thickness of overlying Winnipeg Sequence mud and sand.

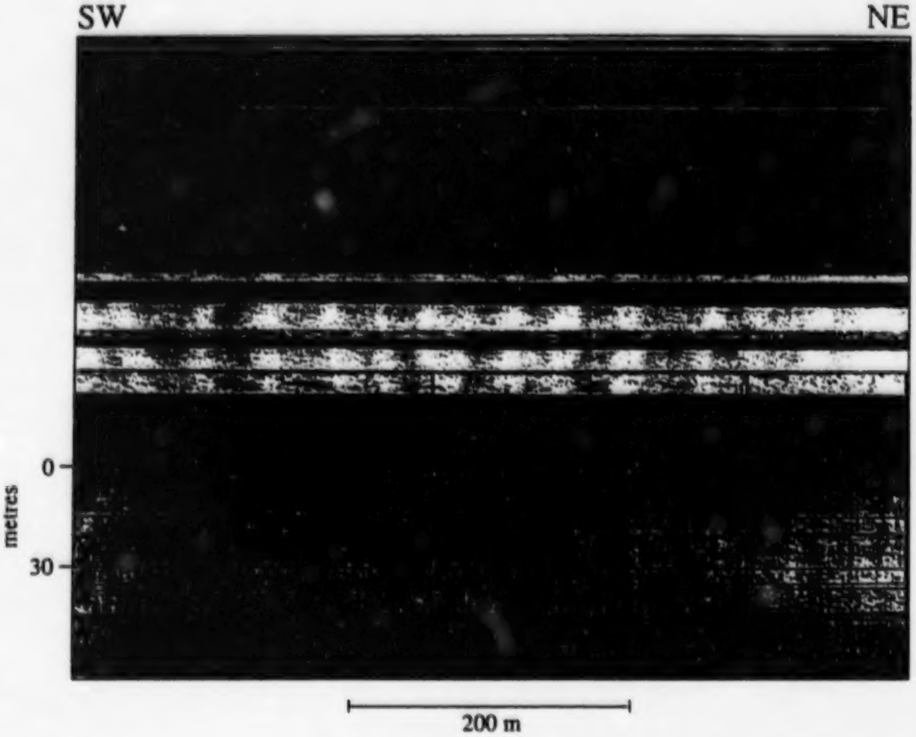

Figure 17. Klein 100 kHz sidescan sonar image showing lakebed ice-scour morphology in Winnipeg Sequence muds on line 130 off northwest shore of Elk Island, South Basin (see Map 1 on CD-ROM and Maps 1-2 and 1-3 in Appendix 10.1).

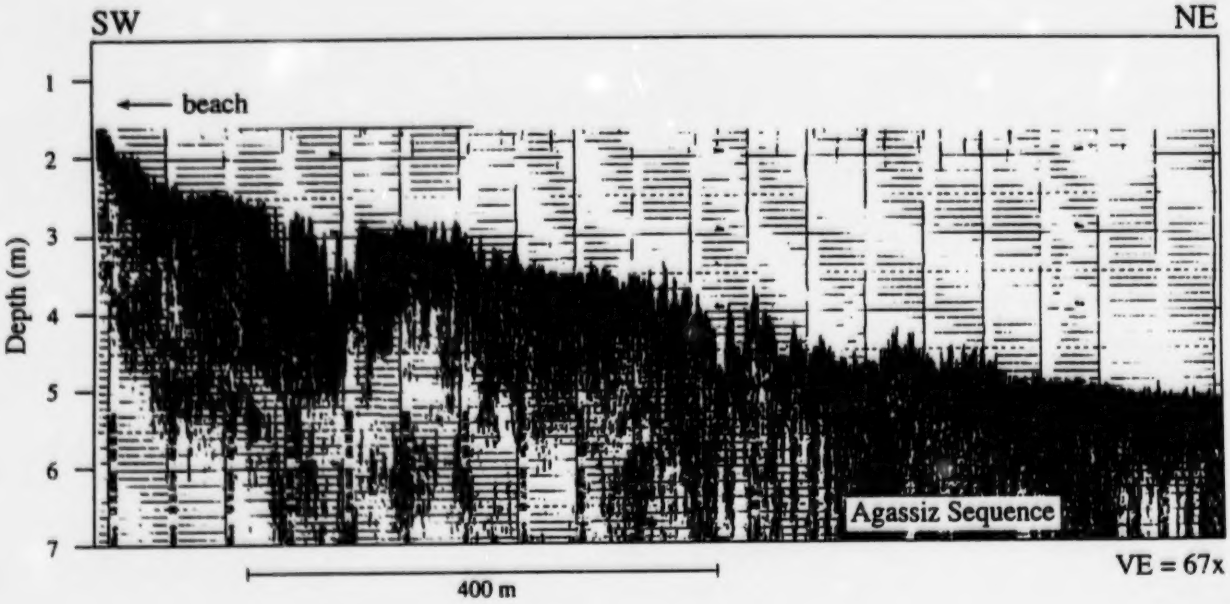

Figure 18. 28 kHz sounder profile (part of line 118) off northeast-facing beach at Willow Point, south of Gimli (see Map 1 on CD-ROM and Map 1-1 in Appendix 10.1). High-frequency noise (ragged appearance) is due to wave motion at time of survey, but rough surface truncating Agassiz Sequence deposits is clearly evident, including scour holes (or trenches) with local relief of almost 1 m.

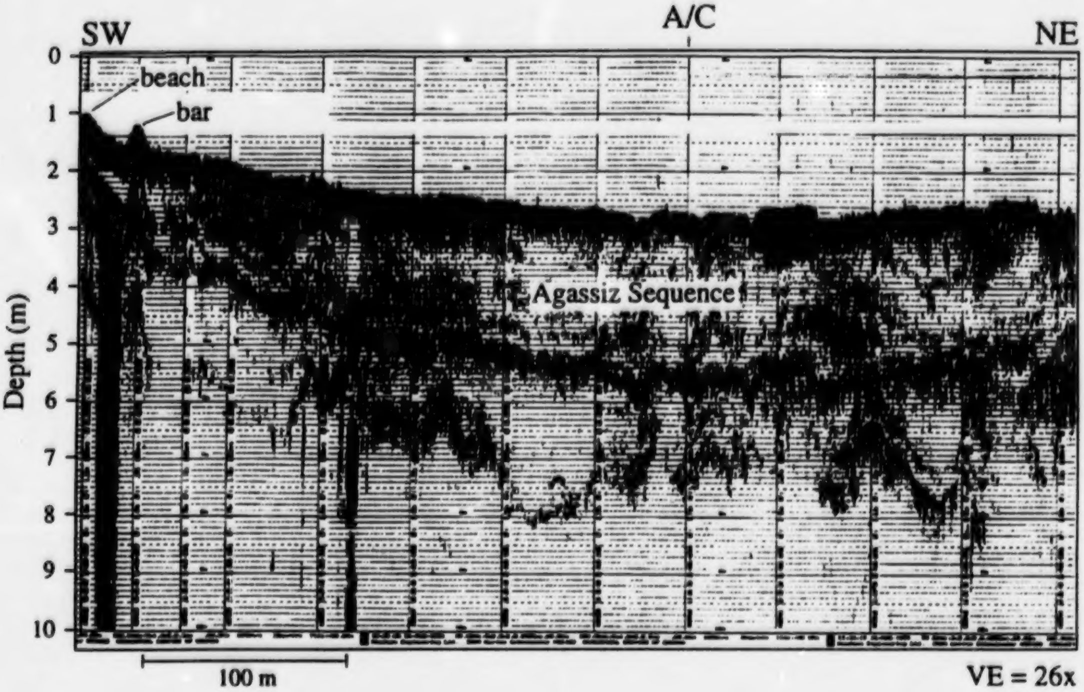

Figure 19. 28 kHz sounder profile (lines 205 and 206) off Sans Souci (see Map 1 on CD-ROM and Map 1-13 in Appendix 10.1), showing restricted lakeward extent of beach and bar sands, with shallow erosion surface cutting Agassiz Sequence deposits in the nearshore.

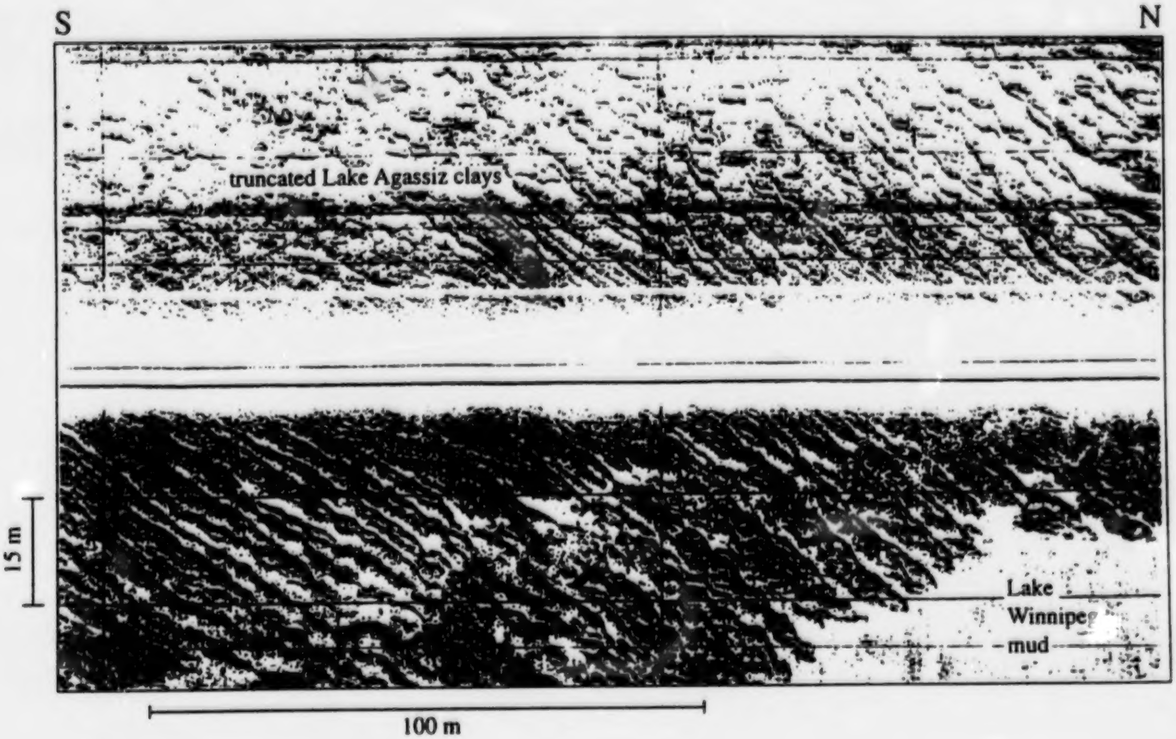
S
N
truncated Lake Agassiz clays
15 m
Lake
Winnipeg
mud
100 m

Figure 20. Klein 100 kHz sidescan sonar image showing dipping Agassiz Sequence strata irregularly truncated at the lakebed along line 211 off Matlock, north of Sans Souci (see Map 1 on CD-ROM and Map 1-13 in Appendix 10.1). Note feather edge of Winnipeg Sequence mud overlying Agassiz deposits in the lower right.

6. Lithostratigraphy

6.1 Architecture, age and lithology of sediments in Lake Winnipeg; seismostratigraphy, long-core lithostratigraphy, and basin evolution

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ABSTRACT

On the basis of seismostratigraphic evidence, the sedimentary fill of the Lake Winnipeg basin is readily divided into two sequences — the Winnipeg sequence overlying the Agassiz sequence — separated by the regional Agassiz Unconformity (Todd et al., 1998). Sediment cores were collected in 1994 and 1996 from 33 sites to sample these sequences and the inter-sequence regional Agassiz Unconformity. Coring operations using marine-type split and solid piston corers and gravity corers, were constrained by the shallowness of the lake and the ship's restricted deck size to a 9-m maximum core pipe. After assessing the performance of the various cores and corer types, the depth/elevation of the mud-buried Agassiz Unconformity was found to be most accurately determined by high-resolution seismic reflection using measured sediment sound velocity.

Low-frequency sleeve gun and high-frequency Seistec seismic profiles show that till is mostly thin or absent over bedrock. The Agassiz Sequence is subdivided into four intervals (Basal, Transparent, Segmented, and Higher Reflective Intervals) in the southern basin and three intervals (Lower, Middle and Upper Reflective Intervals) in the northern basin by the repeated appearances of high-amplitude coherent parallel reflection facies which are associated with silt laminations in silty clay glaciolacustrine sediment, and which are interpreted to mark episodes of ice-marginal proximity and/or enhanced meltwater and sediment discharge. The Agassiz Sequence was locally disturbed south of Long Point prior to 8.9 ka (as indicated by a radiocarbon date from the deposits), possibly by a surge and loading of ice.

Erosion implied by the Agassiz Unconformity is thought to have occurred at different times. Erosion by shallow-water wave abrasion in late phases of Lake Agassiz, was followed by erosion in early postglacial low phases and closed lowstands of Lake Winnipeg. Erosion also occurred in the shoreface of Lake Winnipeg, and continues at present. Reflections in the Winnipeg Sequence show ubiquitous onlap, consistent with deposition in southwardly transgressing lakes with northern outlets subject to glacioisostatic northeast-directed up-tilting.

Tilting and uplift of the Lake Winnipeg basin was modelled as a negative exponential function of age with a relaxation time of 3500 calendar years. This model, based on the deformation of the Burnside level of Lake Agassiz and postglacial shorelines of Lake Winnipegosis, shows good agreement with the independently dated rebound-driven diversion of the Saskatchewan River to Lake Winnipeg at 4.7 ka.

Closed-lake conditions in sub-basins of early Lake Winnipeg arose from a reduced water supply due to a relatively arid early-mid-Holocene climate, diversion of the Assiniboine River to Lake Manitoba, and the absence of Saskatchewan River inflow which bypassed Lake Winnipeg. These conditions dried up the southern basin about 7.5 to 4 ka, and induced a lowstand in the northern basin from about 6.8 to 4.7 ka. The indicators of these past environments comprise a widespread desiccation zone on the Agassiz Sequence surface and radiocarbon-dated evidence of a delay of several thousand years in the onset of Lake Winnipeg sedimentation in the southern basin. Closure of the northern basin prior to 4.7 ka is supported by evidence for long periods of oxygen isotopic enrichment indicating substantial lake surface evaporation.

Analogue modern climates for the dry mid-Holocene conditions were found in the western Canadian prairies by reference to the vegetation history of the Lake Winnipeg area. According to water balance considerations, lake areas which could be supported in sub-basins by the analogue climates were less than the potential open (overflowing) lake areas computed by the tilting model, confirming the mid-Holocene closed lake status for the northern and southern basins.

With the onset of a moister climate and diversion of

the Saskatchewan River to Lake Winnipeg between 5 and 4 ka, lakes in sub-basins became open and overflowed their outlet sills to the north. Continued basin tilting due to glacioisostatic differential uplift raised relative lake levels. The northern basin waters backfloooded and coalesced with the southern basin waters about 2.9 ka, bringing the water surface to a common transgressing level throughout Lake Winnipeg, as at present.

INTRODUCTION

A major objective of the Lake Winnipeg Project is to obtain evidence for the evolution of Lake Winnipeg as a basis for understanding modern long-term trends in water level change and shore erosion. In particular, evidence is sought to allow confirmation or modification of the geological hypothesis that Lake Winnipeg, throughout its history, has progressively deepened and transgressed southward relative to its basin. This is thought to have occurred mainly by northerly uptilting of the lake outlet as a result of glacial rebound (Teller and Thorleifson, 1983; Lewis and Todd, 1996a). Evidence is also required to determine whether climate change, especially warmer and drier conditions in the mid-Holocene, influenced the lake history (Todd et al., 1996, preface to Open File 3113). Other objectives include a better understanding of the underlying geological structure of the basin, and the location of accumulations of fine-grained sediments which might contain fossil or chemical evidence of former lake conditions including the distribution and history of contaminant inputs.

To achieve these general objectives, seismic reflection profiles were obtained in 1994 and 1996 across most of the known basins or sediment depocentres as defined by Brunskill and Graham (1979) and shown in Figure 1. After assessing the stratigraphy of lake-bottom sediments as imaged in the high-resolution seismic profiles, core sites for 1996 were selected in all parts of these transects in order specifically to:

- sample and explain seismic reflectors;
- sample sediments, especially basal sediments over the Agassiz Unconformity.
- sample a complete section of glacial Lake Agassiz sediments;
- determine the age of onset of basin sedimentation in Lake Winnipeg;
- build an uplift model to describe basin tilting with time using the evidence of Agassiz and post-Agassiz warped shorelines;
- test for southward transgression of Lake Winnipeg as computed by the uplift model;
- evaluate water balance effects of climate change and river diversions on the evolution of Lake Winnipeg;

The distribution of 1996 cores complemented and completed the network of 12 cores obtained in 1994 (Lewis and Todd, 1996b).

METHODS

Long cores of 10-cm diameter were recovered in 1996 from CCGS *Namao* at 21 sites using a 6-m or 9-m piston coring device. These were the maximum lengths which could be attempted given the relatively shallow water of Lake Winnipeg and the deck space of CCGS *Namao*. Using a 2-m core pipe, gravity cores, also of 10-cm diameter, were obtained at 20 of the piston coring sites and at one additional site. Two Van Veen grab samples were also collected. The coring operations are described in greater detail in section 4.4 of the cruise report (Todd, this volume). Core locations are shown in Figure 1.

The cores were maintained in a sealed, upright, cool condition while in transit and in cold storage at the core processing facility of the Geological Survey of Canada in Dartmouth, N.S. Non-intrusive tests, including X-radiography on video cassette, gamma ray attenuation (bulk density), magnetic susceptibility and sound velocity were made first on the unopened core liners (Jarrett, this volume). Then, during October 1996, each core was split longitudinally, photographed, described and subsampled. Additional physical properties were obtained, especially colour spectrometry, and a few whole-round core sections of Agassiz sediment were set aside in cold storage for consolidation testing (Jarrett, this volume). Once processed, the core halves were wrapped in plastic film to preserve their moisture, and stored horizontally in D-tubes at 4° C. Access to the cores, their photographs, records of subsampling, as well as other data from the cruise can be arranged with I.Hardy, Curator, Geological Survey of Canada (Atlantic).

RESULTS

Summaries of the gravity and piston core descriptions, and copies of the corresponding high resolution seismic (Seistec) profiles for each 1996 core site are provided in Appendix 10.4 (Lewis et al., this volume); those for the 1994 core sites are in Lewis and Todd (1996b). Long cores from both years are discussed in this report. Abbreviated lithologies for all cores are illustrated in Figure 2 which positions them in south-north order on a depth/elevation scale. Reflections in the Seistec high-resolution seismic profiles are well suited for comparison with core lithology as they record most attributes of the sedimentary sequences down to bed separations of a few tens of cm. The lower resolution limit was demonstrated at site 220 where the long core recovered a 9-cm bed of sand within mud which was not recorded in the Seistec profile (Moran and Jarrett, 1998).

Sampling of seismostratigraphic units

The seismostratigraphic units of sediments beneath Lake Winnipeg (Todd et al., 1998) comprise a Winnipeg Sequence over an Agassiz Sequence bounded by a regional (Agassiz) unconformity. The Agassiz Sequence is subdivided into four intervals in the southern basin and three intervals in the northern basin, based on the presence, absence and character of a high-amplitude coherent parallel reflection facies. Subdivisions of the Winnipeg Sequence are less distinct but are also recognized, comprising an upper mainly transparent facies, a lower facies with low amplitude, discontinuous, coherent reflections, and a clinoform (sand) facies with high amplitude, sloping reflections found in parts of the southern basin. The seismostratigraphic units and their facies are illustrated schematically in Figure 3 on which are plotted the approximate penetrations of the long cores obtained in 1994 and 1996.

Of 13 long cores in the South Basin, 5 cores bottomed in sands of the Winnipeg clinoform subunit (224, 219, 218, 220 and 115) and 8 cores penetrated to various intervals of the Agassiz Sequence. Two cores bottomed in the Higher Reflective Interval, 5 in the underlying Segmented Reflective Interval, and one penetrated to the next lower Transparent Interval. All cores sample the upper and lower subunits of the Winnipeg Sequence. These units are conformable except at site 217 where an unconformity occurs within the Winnipeg Sequence above the Agassiz Unconformity. This site is unique in that it is higher in the basin than other core sites, located on the northern basin margin on its rise to Hecla and Black Islands.

Only three long cores were sited in the constricted central region of Lake Winnipeg. Two penetrate to the Agassiz Sequence, here undifferentiated. Core 113 penetrated only the upper part of the Winnipeg Sequence.

In the North Basin, south of Berens Island, cores 214, 213 and 110 penetrate to an undifferentiated Agassiz Sequence. Between Berens Island and Long Point, cores 209, 208 and 207 all penetrate to the Agassiz Sequence, the latter two bottoming in the Upper Reflective Interval. Core 107, north of George Island, also penetrates to the Upper Reflective Interval.

Of the 10 cores in the northern North Basin, 104 and 203 bottomed in the lower part of the Winnipeg Sequence while the remaining 8 penetrated to the Agassiz Sequence. Cores 201 and 202 penetrate to the Agassiz Sequence (to a level likely equivalent to the Upper Reflective Interval) in the western part of the North Basin. Core 103, in the central part of North Basin samples the Middle Reflective Interval of the Agassiz Sequence. The remaining 5 cores together sample the complete Winnipeg and Agassiz Sequences in the northeastern sector of North Basin. Core 204 is uniquely located at one of the few sites where the Agassiz Unconformity is absent and the core sampled a conformable sequence through the Winnipeg Sequence to the Upper Reflective Interval of the Agassiz Sequence. The other cores penetrate the Agassiz Unconformity: Core 205 to the Upper Reflective Interval, core 106 through the lower part of the Upper Reflective Interval and upper part of the Middle Reflective Interval, core 206 through the Middle Reflective Interval, and 105 through the Lower Reflective Interval into till over the Acoustic Basement.

Corer performance and mud shortening

Slightly different modes of core collection, variations in corer operation, and natural variations in sediment strength lead to variations in the recovery of sediments, particularly the soft, low-strength Lake Winnipeg mud. In 1994, a long gravity corer was used after loss of two standard solid piston corers. In 1996, a split piston corer was used followed by the standard solid piston corer as described in the 1996 cruise report (Todd, this volume).

In this section we examine the recovery of mud by comparing the recovered length of mud in each core for both 1994 and 1996 cruises with the thickness of mud measured by the Seistec high-resolution seismic profiler (Table 1). The acoustic time of travel through the mud as scaled from the Seistec profile at each core site was divided by the velocity of sound as measured in the cores to convert travel time to mud thickness (Table 1). The profiler (acoustic) method is preferred for measuring mud thickness as it avoids the mechanical forcing of the coring process which may cause soft sediment to consolidate or bypass the cutter. The differences in mud thickness determined by acoustic and coring methods are given in Table 1 and illustrated in the bar graph of Figure 4. The core sites are arranged from south to north. In most cases the mud lengths in the cores were less than the acoustically measured thicknesses, as expected. For the 29 cores for which data are available, 6 (21%) mud thicknesses were virtually equal with differences < 20 cm. All were of the solid piston type. The mud thickness differences at most sites were <1 m (22 cores, 76%). Only 2 (7%) were greater than 2 m, and the mud in one long gravity core was 3.4 m less than the acoustically measured thickness.

The performance of the coring operation at each site was estimated by noting the length of mud adhering to the outside of the core pipe in comparison with the length of core recovered. This measure is generally interpreted to indicate the depth of core pipe penetration below the lake floor, although a misleading value can be obtained if the corer has fallen over (too long), or if some adhering sediment has been washed off (too short). A core recovery ratio was determined by dividing the total recovered core length by the apparent penetration. See Todd (this volume) for discussion of core recovery ratios for the 1996 cruise. Ideally the recovery ratio should be unity; lesser ratios indicate a loss or compaction of sediment in the coring operation. Core recovery ratios for most long core sites, both 1994 and 1996, are listed in Table 1.

The mud thickness differences as determined above are plotted from Table 1 against the core recovery ratios for each corer type in Figure 5 to illustrate the relationships among these parameters for the set of Lake Winnipeg cores. Data were available for this type of plot for 28 of the 33 long core sites. The 4 long gravity core sites show an approximate inverse correlation between mud thickness shortening and recovery ratio, ranging from less than 1 m of shortening at unity recovery to 3.44 m shortening at 0.49 recovery ratio.

The split piston corer results were poor in recovery ratio (all but one were < 0.8), but were fairly consistent in mud shortening, with modest values mostly < 1 m. At site 205 it is possible, by correlating the gravity and piston core lithologies (Appendix 10.4, this volume), to show that 92 cm of the upper part of the Lake Winnipeg mud section was lost or compressed in the split piston core. Assuming the apparent penetration of 886 cm is correct, a further 257 cm of shortening occurred in the piston core to account for the difference between penetration and core length. This apparent shortening is consistent with the presence of microfaulted rhythmic laminations observed in the Agassiz portion of the core.

The solid piston corer shows the best results. Except for site 218, all of these cores exhibit a recovery ratio of 0.8 and greater. At 218, thin mud over sand is thought to have allowed the corer to fall over and contaminate the value observed for apparent penetration. However, some of these cores show rather high values for mud shortening (three greater than 1 m). Most of the core shortening appears to have occurred in the mud section as illustrated by site 213 where comparison with the gravity core log indicates at least 146 cm shortening in mud, or up to 281-15=266 cm shortening in mud according to the acoustic mud thickness determination. At most sites the apparent shortening is less than one metre for the solid piston corer. The higher quality of this corer is consistent with its recovery of well-preserved, non-deformed laminated sediments.

Architecture, lithology and origin of Agassiz Sequence reflectors

South Basin

A generalized picture of the stratigraphic relations of seismic units and their lithology is given in Figure 6 for the southern basin. Over the bedrock surface, which is of Precambrian metamorphic composition in the east and Paleozoic sedimentary rock in the west (Todd et al., 1998), subglacial sediments are thin or absent except at morainic ridges (e.g. Pearson Reef) where the inferred sediment is relatively thick.

The Agassiz Intervals overlie the basin floor and lap onto or drape the morainic ridge in their order of deposition — Basal, Transparent, Segmented and Higher Reflective Intervals. The Basal Reflective Interval was not sampled beneath the lake. Correlative shore-cliff exposures suggest this Interval consists of a layered lithology of alternating decimetre- to centimetre-scale beds of sorted and cross-bedded silt and laminated silty clay (unpublished observations by D.L. Forbes and C.F.M. Lewis, 1997), apparently reflecting deposition near an ice front in a glacial lake with alternating regimes of highly concentrated turbidity flows and rainout from sediment plumes, respectively. The core sample at site 121 suggests the Transparent Interval is a deposit of faintly bedded to massive silty clay with calcareous silt clasts and layers, and dropstones. The Segmented Reflective Interval, as seen in core 120, appears to consist of alternating sub-metre-scale units of banded to massive silty clay and centimetre-scale laminated silty clay rhythmites with thin calcareous silt layers and lenses. Core 119 samples the Higher Reflective Interval and suggests it comprises a sequence of sub-centimetre- to centimetre-scale couplets (rhythmites) and banded silty clay, both with silt laminations at 2-20 cm.

Given the above correlations of seismic intervals and lithology, some implications are evident for the origin of coherent reflections in the Agassiz Reflective Intervals. As a general rule, acoustic wave propagation through layered media results in reflections when an acoustic impedance contrast is detected by the waves. Detection usually occurs when the layer thickness exceeds one-quarter the acoustic wavelength. For the Seistec profiling system operating between 2 and 6 or 8 kHz as used in this study, and for the mid-range acoustic velocity of 1515 m/s (1480-1550 m/s) as measured in the Agassiz sections of cores 119-122 by Moran and Jarrett (1996, 1998), the layer thickness must exceed 6-19 cm for reflections to occur. The larger thicknesses in this range are probably required for the Seistec system to record reflections, judging from its inability to image a 9-cm thick sand bed (Moran and Jarrett, 1998).

From the few samples obtained of the Agassiz Sequence sediments, the most obvious lithology and structure for causing the relatively closely-spaced coherent reflections are composite layers with differing impedance contrasts made up of groupings of silty clay rhythmites as in core 120. In addition, combinations of laminations of sorted silt or sand as in cores 119 and 217, either alone or with layered structure (e.g. rhythmites) of the host silty clay, might also form aggregate layers of differing acoustic impedance. For resolution in the Seistec records, the aggregate layers must be between 9-19 cm thick or thicker. One example where reflections from a group of rhythmites are illustrated is core 120, which intersects coherent reflections in the Segmented Reflective Interval. The lithology is a diffusely banded silty clay from 196 cm to 354 cm with an interbed of silty clay rhythmites from 245-318 cm. The likelihood of a reflection from the boundaries of these units is calculated from the contrast in their acoustic impedances which is calculated as the difference in products of their unit average bulk densities and sound velocities (Telford et al., 1990). The physical properties for the core (Moran and Jarrett, 1996) show lower bulk density (1.65 vs 1.73 Mg/m^3) and lower sound velocity (1520 vs 1535 m/s) in the rhythmite section, such that their product (2508) or acoustic impedance is 6% lower than the product of density and velocity (2656) in the diffusely banded section below. The reflection coefficient, R, is calculated as the ratio $(Z_2-Z_1)/(Z_2+Z_1)$ where Z = acoustic impedance of unit 1 above, and unit 2 below the reflecting boundary. Using products for impedance values, R = 0.029 for the boundary between rhythmite and non-rhythmite sections in core 120 (Table 2). As reflection coefficients in rocks are commonly less than 0.2 (Allaby and Allaby, 1991), it is quite possible for this sediment boundary to generate a modest acoustic reflection. Furthermore, the downcore boundary between non-rhythmite and rhythmite units in this case would present a negative coefficient of -0.029, and this would signify a phase reversal in the acoustic wave at the reflector. This means that the reflecting surfaces within the Segmented Reflective Interval of core 120 would be represented in the graphic Seistec record by reflections of similar amplitude but of opposite phase. Similarly, the bulk density profile of core 119 shows contrasting layers of 1.83 and 1.90 Mg/m^3 within the Higher Reflective Interval where it encounters sub-cm-scale silty clay rhythmites with silt laminations. Although sound velocity values were not obtained and acoustic impedances could not be calculated for this section of core, the magnitude of change in bulk density is similar to that for core 120 and it is quite possible that reflections would be generated (Table 2).

It should be noted that the output pulse from the seismic source consists of several oscillating cycles of diminishing amplitude. These are revealed on the graphic Seistec record as a series of parallel, conforming, thin black lines with the first cycle being strongest and darkest, for example, the lakefloor reflection at sites 201, 202, 217, 218, 219 and 220 (Appendix 10.4, this volume). Each subsurface reflecting boundary may also yield a similar package of parallel lines. Additional lines can also be generated by interference or by internal reflections between reflecting boundaries. Thus the many reflections (dark lines) on a graphic seismic profile can be accounted for by a much fewer number of impedance boundaries within the sediment column. The identification of real geological boundaries requires a certain measure of geophysical interpretation.

The facies of coherent reflectivity is well expressed in the Basal Reflective Interval which immediately overlies glacial deposits in the Pearson Reef moraine (Fig. 3). Because the facies consists of layered sediment it was deposited in standing water. Given the correlative shore-cliff exposures described earlier, and its post-morainic (ice marginal) stratigraphic position, this facies represents deposition near the ice margin in a glacial lake with a seasonal meltwater regime. We speculate that the absence of closely spaced reflections in Seistec profiles indicating lack of detectable contrasts in acoustic impedance, as in the overlying Transparent Interval, implies the absence of rhythmites and silt laminations associated with this might be retreat of the ice margin and a reduction in the output of meltwater and coarse (silt) sediment dispersal as highly concentrated turbidity flows, i.e. a more distal position of deposition relative to the ice front and its sediment-producing processes. Transparency possibly could also result from disturbed or chaotic deposition such as by debris flowage or glacial over-ride. A reappearance of the coherent reflection facies higher in the section, as in the Segmented and Higher Reflective Intervals, possibly implies the return of ice-marginal, seasonally controlled meltwater and coarse sediment (silt) input. A stratigraphic implication of relating the coherent reflection facies to silt deposition near a northward retreating ice margin is that the facies will be time-transgressive, somewhat younger at its northern occurrences than at its southern occurrences depending on the rate of ice retreat and sediment output.

The seismic stratigraphy of the South Basin (Fig. 6) indicates that the Agassiz Intervals followed a subglacial environment as they overlie ice-marginal deposits (e.g. Pearson Reef moraine). With their layered structure, the sedimentology and stratigraphy of the Intervals suggest they denote deposition in proglacial lake environments which followed the northward retreat of the Laurentide Ice Sheet, as mentioned above. The proglacial lake was that of Lake Agassiz as understood from its many other deposits and shorelines now onshore (see Teller and Clayton, 1983, and Teller et al., 1996, and papers and references therein). The depression for the ice-marginal lake was enhanced by crustal isostatic depression under the ice load; meltwater and runoff were impounded by ice to the north and by the rise of the land surface to the south. The most recent synthesis of the drainage and water level history of Lake Agassiz (Thorleifson, 1996) suggests that the South Basin was inundated by deep water (>50 m) between about 11.1 and 9 ka BP. It is conceivable that ice readvances north of the southern basin in this history at about 10 and 9.3 ka BP led to deposition of the coherent reflection facies in the Segmented and Higher Reflective Intervals of the southern basin. Subsequent ice retreat lowered Agassiz lake levels and progressively reduced water depths in the southern basin to a few tens of metres or less. This condition probably enhanced wave and current erosion of the previously deposited Agassiz Intervals. This erosion led to the onset of formation of the widespread regional Agassiz Unconformity. From the inferred history based on onshore evidence (Thorleifson, 1996), the southern basin was finally isolated about 8 ka BP or earlier.

Processes of glaciolacustrine sedimentation have been discussed previously for the Transparent and Segmented Intervals (Todd et al., 1998). The Transparent Interval may consist of unstratified sediment or may actually contain thin (i.e. <20 cm) reflectors which were not resolved by the Seistec profiling system. Alternately, or in addition, original layering was destroyed by dewatering, degassing, glacial override, or lake ice scour. Similar processes are speculated to account for reflector offsets in the Segmented Reflective Interval. In addition to Figures 12, 13, 15 in Todd et al. (1998), the seismic profile for site 223 (Appendix 10.4, this volume) illustrates the characteristic poor definition of the Transparent Interval and offset reflectors in the Segmented Interval. Offset reflectors in the configuration of an upward-pointing cone on the northern side of the site 223 profile are especially suggestive of a water/gas escape feature. A gas mask directly over this feature within the overlying Winnipeg Sequence indicates that venting may have occurred in Late Holocene time.

North Basin

The principal stratigraphic relationships as seen in Seistec and sleeve gun profiles in the northern basin are summarized in Figure 7, especially for the sub-basin north of Long Point. A major bedrock boundary, which trends generally N-S, underlies the deepest part of the basin. To the east is the Precambrian metamorphic rock surface of the Canadian Shield with an undulating relief up to 35 m. To the west are the onlapping Ordovician sedimentary rocks of the Interior Plains, here mainly dolomite and limestone, which dip gently southwest to the Williston structural basin (Todd et al., 1997, 1998).

The Agassiz Sequence directly overlies bedrock in most seismic profiles. In places, a seismic unit with high amplitude, incoherent reflectivity is resolved over bedrock beneath the Sequence (Figure 7) as at core site 105 in the northeastern part of the lake (Appendix 7.1 in Todd et al., 1996) where a hard, light gray, stony diamicton with a calcareous sandy matrix was found and interpreted as a subglacial deposit of till. More extensive and thicker units, possibly till also, occur under the Agassiz Sequence over bedrock in the western part of the northern basin, for example, under site 201 (Appendix 10.4, this volume). It also may be inferred that the Agassiz Sequence laps onto glacial deposits of the Hargrave Moraine (Nielsen and Thorleifson, 1996) now being eroded along the north shore of Lake Winnipeg (e.g. right side of Fig. 7).

The Agassiz Sequence in the northern basin consists of three conformable facies, the Lower, Middle and Upper Reflective Intervals, deposited in succession over the acoustic basement of bedrock or glacial diamicton (till) (Todd et al., 1998). The Lower Reflective Interval (LRI) comprises a relatively thin package of closely-spaced high-amplitude, coherent reflections, similar to the Basal and Higher

Reflective Intervals in the South Basin. The LRI is identified on the seismic profiles at core sites 103-107 and 202-207 inclusive at various points throughout the North Basin. At most sites it is approximately 2 m thick, increasing to about 5 m at site 207 southwest of George Island. Density differences that may be indicative of reflection generation are noted in the base of core 206PC which penetrates to the LRI (Table 2). At site 105 where the Interval was well sampled, the reflectivity appears to be related to a 1.6-m interval above till containing white silt partings, grit and dropstones within sub-cm silty clay rhythmites. Fine-grained cm-scale reddish bands appear within this interval also (Appendix 7.1, Todd et al., 1996). Within this interval the physical property logs (Moran and Jarrett, 1996) show two layers of slightly elevated density and velocity which indicate differences in acoustic impedance that yield reflection coefficients of 0.043 at their boundaries (Table 2). These coefficients indicate that reflections are generated within the basal rhythmites.

The Middle Reflective Interval in Seistec profiles consists of a package of two or more strong coherent reflections commonly 2-5 m thick, over a transparent facies ranging from about 5 m to over 15 m in depressions. Reflectivity is better imaged and the Interval often appears thicker over flat portions of the profiles, and thus thickness variations are, in part, a function of reflector configuration. Where best sampled, at site 106, the seismic facies is 3-4 m thick but is dominated by two strong, multi-cycled reflections separated by about one m. In core 106PC, the reflectivity facies correlates with a 2.8-m thick zone of relatively thick, cm-scale, silty clay rhythmites containing numerous white silt partings. The coarse fraction is less evident in the thinner, mm-scale, silty clay rhythmites above and below the zone with silt laminae. The likelihood of reflections originating in this zone is supported by the physical property measurements in the core where two intervals (300-330 and 390-430 cm) show higher density (1.75 Mg/m^3) and higher velocity (1500 m/s) than their surrounding sediments (about 1.55 Mg/m^3 and 1450 m/s). These values yield products (impedances) of 2625 and 2248 and a reflection coefficient of 0.077 (Table 2). For the thicknesses over which they occur, acoustic reflections are quite likely to be generated at these impedance boundaries. Long cores at four other sites also penetrated or encountered the strong coherent reflections of the Middle Reflective Interval. At the depths where the reflections are encountered, the core lithology indicates thicker silty clay rhythmites commonly with thicker laminated gray layers having silt lenses or laminae. These zones also show zones or spikes of increased bulk density (differences of 0.08-0.2 Mg/m^3) and, where measured, associated increases in sound velocity of about 22-50 m/s, with reflection coefficients ranging from 0.031 to 0.056 (Table 2). Thus, the thick rhythmite zone with silt laminations is associated with acoustic impedance changes, and is the likely source of the strong coherent reflectivity in the Middle Reflective Interval.

The Upper Reflective Interval comprises an upper zone of parallel coherent reflections over a lower transparent zone as typically shown beneath northeastern Lake Winnipeg by Seistec profiles at sites 103PC and 104PC (Appendix 7.1 in Todd et al.,1996), and at 204PC and 205PC (Appendix 10.4, this volume). The maximum thickness of the Interval is 13 m, 11 m and 10m beneath sites 204PC, 104PC and 202PC in the north, respectively. It thins southward to about 8 m beneath the Agassiz Unconformity in the central North Basin at site 103PC. A URI-like facies about 70 km farther south at sites 107PC and 207PC is also 8 m thick, northwest and west of George Island respectively. The lithology of the upper zone of the URI comprises rhythmically to finely laminated clay and silty clay with silt lenses and laminations at sites 205PC, 207PC and 208PC. At 107PC, the clay was banded with diffuse laminae boundaries (Table 2). The physical properties within this zone contain layers of contrasting density, velocity, and acoustic impedance greater than 20 cm in thickness with boundaries showing reflection coefficients of about 0.02 (Table 2). Thus the URI coherent reflection facies on Seistec profiles likely originates as reflections from boundaries between aggregated layers consisting of packages of banded to rhythmically laminated fine-grained sediment with silt laminations.

The sediments which overlie the acoustic basement (bedrock or till) are regularly laminated to stratified and must reflect accumulation in a water body, specifically glacial Lake Agassiz in this region which accompanied northward retreat of the margin of the Laurentide Ice Sheet across the North Basin. The first sediments over till have been sampled (105PC) and are distinct silty clay rhythmites with grit and silt laminations which are registered in Seistec profiles as the lowermost coherent reflection facies. The overlying transparent facies (lower zone of the Middle Reflective Interval) contains fewer silt laminations. This observation suggests the ice sheet became less productive with respect to silt, possibly due to reduced seasonal melt, northward retreat of the ice margin, or because of an internal shift in sediment source or production. The latter interpretation is possible because the silty clay rhythmite thicknesses (Appendix 10.11, this volume) do not change much across the LRI-MRI boundary at about 350 cm in core 105PC whereas many geochemical parameters do change (Appendix 7.4, Todd et al., 1996).

After the foregoing period of moderate sedimentation, the basin was filled with a series of thick centimetre-scale rhythmites with abundant silt laminations which register, in aggregate, as coherent parallel reflections in the upper zone of the Middle Reflective Interval. This substantial increase in meltwater and sediment delivery possibly signifies enhanced subglacial meltwater inflow with ice-streaming in the Laurentide Ice Sheet and a readvance of the ice margin towards the basin. This occurred in the Nipigon basin in northwestern Ontario, where thick rhythmites were deposited during ice advance to the Nipigon moraine (Thorleifson and Kristjansson, 1993). Alternatively, the thicker and siltier rhythmites reflect increased seasonally controlled meltwater input from supraglacial meltwater sources.

The final phase of glaciolacustrine sedimentation is marked by the Upper Reflective Interval, first as transparent facies of thin rhythmites to finely laminated silty clay, then finally as a coherent reflection facies of similar sediment containing silt lenses and laminations (Table 2). The thin rhythmites and laminations in the transparent facies suggest reduced seasonal melt or recession of the ice margin to a more distant position relative to the northern basin. The reappearance of silt laminations in the upper facies of coherent reflections might indicate ice readvance or increased seasonal melt, but because lamination thicknesses do not increase, it is more likely that the coarse grains were introduced by wave erosion and winnowing of existing deposits in a phase of declining lake levels.

A disturbed zone of the Agassiz Sequence exists in North Basin south of Long Point and west of George Island. In this area, the Agassiz Sequence contains recognizable segments of the coherent parallel reflection facies but in most places it is distorted or eradicated, suggesting an episode of loading and slight reworking of the glaciolacustrine sediments (Fig. 8a). A coherent reflection facies equivalent to the URI-like facies at site 207 west of George Island overlies the loaded zone (Fig. 8b). Neither this URI nor the overlying Agassiz Unconformity and Winnipeg Sequence is disturbed, indicating that the loading occurred in Lake Agassiz before or in the initial phases of deposition of the URI in this area, possibly by a surge of ice and icebergs from a nearby glacier margin. A depression in the surface of the disturbed facies infilled with URI sediments at time 1657 on the Seistec profile in Figure 8a is suggestive of scour by a large moving iceberg keel. Unfortunately no sample of the disturbed zone was recovered; a piston core was attempted but the coring cable parted and the corer was lost (site 108, Todd et al., 1996).

An AMS date in the URI of 207PC (Appendices 10.4 and 10.6, and Telka, this volume) provides a minimum age estimate for the loading event. This date (9170±70 ^{14}C years BP, CAMS 38677) is on ostracode carbonate valves recovered from the upper part of the URI. Allowing for an estimated correction of 255 years for the hard-water effect (see later section on the age of basal Winnipeg Sequence sediments), the ostracode date suggests the age of late sedimentation in the URI west of George Island is about 8920 ^{14}C years BP or 8.9 ka. The loading disturbance within the Agassiz Sequence occurred prior to this age plus the time to accumulate the URI up to the dated level.

The Agassiz Unconformity and attributes of the Agassiz Sequence surface

South Basin

Truncation of the Agassiz Reflective Intervals and an erosion surface on the Pearson Reef moraine are evident in the seismic profiles and serve to indicate erosion and formation of the Agassiz Unconformity. Offshore, this erosion likely occurred during declining and shallowing phases of Lake Agassiz, but might also have occurred in shallow water of early Lake Winnipeg. The AU is remarkably smooth, generally lacking relief of more than 20 cm in Seistec high-resolution profiles. This suggests that most erosion or the latest phases of erosion occurred by abrasion at the base of wave-driven water circulation, rather than by gouging by iceberg or lake-ice pressure-ridge keels, for example. Nearshore studies (Forbes, this volume) have shown that Agassiz sediments are being eroded today in the shallow-water shoreface of Lake Winnipeg. This modern erosion surface can be traced offshore into the buried AU. Thus the AU is a regional, time-transgressive stratigraphic feature whose formation encompasses erosion processes dating from the late phases of glacial Lake Agassiz to early and present processes in Lake Winnipeg.

The surface of the clay-rich Agassiz sediments beneath the AU is characterized by a thin sub-metre-scale zone of enhanced magnetic susceptibility, higher shear strength and higher bulk density (Moran and Jarrett, 1996; 1998; Jarrett, this volume), lower water content (Last, 1996), and/or by a distinctive crumbly, dry texture (Fig. 9) (see core logs for site 120 in Appendix 7.1, Todd et al., 1996, and sites

221, 222, 223 in Appendix 10.4, this volume). These properties suggest an effective period or periods of desiccation of the eroded Agassiz Sequence surface before deposition of the overlying Winnipeg Sequence. By analogy with dry zones in the nearby Lake Manitoba sediment record, the desiccation is most likely to have formed by pedogenesis related to periods of extremely low (or no) water (Last and Teller, 1983). Other processes, such as seasonal freezing of shallow water to the bottom have been considered (Teller and Last, 1981; 1982).

One core (223) contains over 0.5 m of reworked Agassiz sediment with included lenses and balls of organic fibres and macrofossils which represent shallow water conditions with occasional drying (Telka, this volume). This finding suggests that a zone of reworked seasonal pond sediment may immediately underlie the AU. The zone is likely discontinuous as it has only been recognized at this one core site. One process which could account for the reworking is ploughing by wind-driven keels or bases of seasonal ice floes in a shallow environment.

Initially, chanelling and channel fill facies in the uppermost Agassiz Sequence were expected on the assumption that the early Red River and its tributaries would have extended northward. This speculation followed from the inference that most of the Basin would have been drained and subaerially exposed upon its isolation from Lake Agassiz, except for a small residual impoundment in the north behind a broad rise in the bathymetry (sill) between Hecla and Black Islands. This condition results from the Basin's downtilted configuration to the northeast at that time, prior to post-Agassiz differential glacial rebound (Nielsen and Thorleifson, 1996; Lewis and Todd, 1996a; Matile et al., 1996; Todd et al., 1997). Although the survey grid was sparse and gas masking occurred on 60% of the available line coverage in South Basin (Todd et al., 1998), the only discovery of a potential channel and channel fill was on the Hecla-Black sill at site 217. More survey lines in this area are required to demonstrate whether this depression is an outlet channel, or an isolated depression. If it is an outlet drainage channel, it must have operated before it was filled with the two sediment units documented at site 217 which are younger than 4 ka. See Forbes et al. (this volume) for a more complete description and interpretation of this site.

North Basin

The Agassiz Sequence reflectors are truncated almost everywhere beneath the Winnipeg Sequence by the remarkably smooth, planar, and regional Agassiz Unconformity (AU) (Fig. 7). Small areas of deposition, more than 20-27 m below lake level, in lows over depressions in the underlying bedrock relief lack reflector truncation (see Seistec profiles for sites 204 and 203, Appendix 10.4, this volume), and show conformable reflections through the Agassiz-Winnipeg Sequence boundary. Core 204PC was sited at one of these areas where the AU is absent at depths greater than 20 m below present lake level; it recovered a complete section of the Winnipeg Sequence. Together with core 205PC nearby which samples the upper part of the URI and subsequent early Lake Winnipeg sediment beneath its AU, these cores provide a sedimentary record of the transition from Lake Agassiz to Lake Winnipeg in the northeastern sector of North Basin. In North Basin, the AU is considered most likely a result of wave erosion in declining phases of Lake Agassiz, in early phases of Lake Winnipeg, in subsequent lowstands during closed-lake conditions (Lewis et al., this volume), and in the modern shoreface.

Seismic facies, stratigraphy and lithology of the Winnipeg Sequence

South Basin

The Winnipeg Sequence which overlies the AU is divisible into lower and upper facies. The upper unit is nearly transparent with a few discontinuous zones of reflectivity whereas the lower unit commonly shows low-amplitude, discontinuous, coherent reflections. The boundary between these units is conformable, gradational and indistinct. This zonation of the Winnipeg sequence is well-illustrated in the Seistec profiles for core sites 220 and 223 (Appendix 10.4, this volume) and 115, 121 and 122 (Appendix 7.1 in Todd et al., 1996). The lithology of cores at these sites indicates the Winnipeg Sequence consists of soft silt-clay to clay mud in the offshore basin, with the lower part, which is equivalent to the lower seismic facies, containing more occurrences of banding, and silt lensing and lamination. Grain size analyses by Henderson and Last (1998) show that the lower Winnipeg Sequence sediments at sites 121 and 122 also contain more silt and sand than the upper sediments (70% vs 50-60%). A distinctly larger fraction of coarse sediment (65-85%) exists in Lake Winnipeg mud at site 120 in Traverse Bay on the east side of the basin. Here, the seismic profiles of the Winnipeg Sequence are more reflective (darker) than at mid-basin sites. Overall, the greater reflectivity of the lower Winnipeg seismic facies is consistent with a larger silt and sand content within the Lake Winnipeg mud.

A subfacies of the Winnipeg Sequence consists of planar and ridged reflective bodies containing clinoform reflectors over the AU. It is best recorded in the northern part of the basin (sites 115, 218, 219 and 220) but also occurs in the south (site 224). The northern occurrence of the subfacies is found adjacent to morainic deposits (Pearson Reef moraine). The sediments of the subfacies comprise well sorted sand with a few graded gravel beds. They underlie and prograde over basinal mud of the lower facies of the Winnipeg Sequence. See also Forbes et al. (this volume) for a fuller description and interpretation of the South Basin mud-buried sand facies. These sands are interpreted as evidence of nearshore and shoreline deposition when water levels were rising from about 15 to 13 m below present mean lake level after 4 ka BP.

North Basin

Similar to the South Basin, the Winnipeg Sequence is divisible into an upper nearly transparent facies and a lower more reflective facies with discontinuous reflections. The boundary between these facies is transitional. In places, the lowest part of the lower facies contains high-amplitude continuous reflections as at site 204PC (Appendix 10.4, this volume). Here, the core lithology below 450 cm suggests these reflections originate with impedance contrasts between layers containing groups of silt and fine sand laminations in mud. In the Seistec profile for site 204PC, the high-amplitude reflections lap onto the unconformity on the Agassiz Sequence over an adjacent high to the northwest. This onlap indicates transgression of an early phase of northern Lake Winnipeg dated at 6750±70 ^{14}C years by an AMS age determination (CAMS 38678) on a spruce needle at 513-518 cm in core 204PC (Appendix 10.6 and Telka, this volume). Erosion and winnowing of highs in the Agassiz Sequence by waves and currents in this transgressing low-level lake likely supplied the sand and silt found in the lowest part of the Winnipeg Sequence. The overlying lower amplitude reflections in the lower facies correlate to zones of diffusely banded mud with sporadic pods and lenticular units of millimetre-scale silt laminations in core 204PC which exhibit pronounced variations in bulk density and magnetic susceptibility below 250 cm (Appendix 10.3, this volume). Above 250 cm in core 204PC, which correlates with the transparent upper seismic facies of the Winnipeg Sequence, the fine-grained mud contains few silt laminations and shows relatively smooth trends in its downcore physical properties. The lithological correlations at 204PC for the transparent upper facies and the low-amplitude, discontinuous reflection subfacies of the lower seismic facies of the Winnipeg Sequence are typical, and are repeated at most other core sites in the North Basin.

Basal Winnipeg Sequence sediments; implications for evolution of Lake Winnipeg

Here, we consider the depth and elevation, seismic stratigraphy, lithology and age of the basal Winnipeg Sequence sediments in relation to predictions of long-term water-level trends by working models of glacial rebound and climate change.

Depth and elevation of basal sediments

The depth and elevation of the basal Winnipeg sediments (and the AU) were first adjusted for each coring site to reflect accurate depth below mean lake level (217.4 m asl). This was done using depths measured by acoustic and seismic sounding calibrated by measurements of sediment sound velocity in the cores (Table 3). This procedure eliminates the effects of shortening in the mud section caused by sediment bypassing or compaction during the coring process (Table 1, Figs. 4 and 5). The shortening would cause the basal sediment and the AU to be plotted erroneously at slightly shallower depths (by 0.5-2 m in most cases). The largest error (3.4 m) occurred in core 122. Unfortunately, this problem was not recognized in 1996 when the age and elevation of the basal peat in this core was used to test predictions of water-level trend by glacial rebound (Lewis and Todd, 1996a). The acoustic/seismic-based depths to the AU are used in portraying the summary lithologies in Figure 2.

Seismo-stratigraphy of basal sediments

Seistec reflection profiles at each of the core sites were examined for details of lap out or baselap of reflections at the base of the Winnipeg Sequence (Appendix 7.1, Todd et al., 1996; Appendix 10.4, this volume). Baselap is the discordant relationship marking the lower boundary of a depositional sequence, where upper beds (reflections) lap out over the underlying surface, either as onlap where overlying beds thin updip, or as downlap where overlying beds thin downdip (Allaby and Allaby, 1991). At some sites basal reflections are too discontinuous or incoherent to determine baselap relations and at others basal reflections parallel the AU so that lap outs are not evident. However, at fifteen profile sites baselap relations were evident (Table 4). All show onlap, a condition that indicates a basin evolution of either land subsidence or transgression (Allaby and Allaby, 1991). Either process will tend to cause shorelines and sediment sources to recede from the offshore site, and increase space for deposition as implied by the development of an onlapping sequence. Because the whole region is undergoing uplift due to glacial rebound (Lambert et al, 1998; Tackman et al., 1998; Teller and Thorleifson, 1983), subsidence is unlikely, and the evidence of onlap indicates that basal sediments in Lake Winnipeg were deposited under a regime of rising water level (transgression) from 22 m to at least 12 m below modern mean lake level (Table 4). Onlapping reflections from depth to the modern edge of mud deposition, for example at the Pearson Reef moraine at sites 218, 219, and 220 (Appendix 10.4, this volume), show that transgression continued throughout the depositional history of Lake Winnipeg. However, slight reversals in transgression likely occurred within this history as indicated by a local unconformity, dated 3340 BP, above the AU at site 217 (Appendix 10.4, this volume).

Litho-stratigraphy of basal sediments

The lithology of Lake Winnipeg offshore deposits at every core site which penetrates to the Agassiz Sequence is typified by a fining-upward sequence of muddy sediment (Appendix 7.1 in Todd et al., 1996 and Appendix 10.4, this volume). The basal section consists typically of bedded sand, silt or sand laminations, muddy sand, or just a few sand grains on the basal contact. Mollusc shells, shell hash, or a more calcareous zone often are associated with the basal sediments. The coarse facies is succeeded upward by fewer laminations to more massive silty clay or clay mud, bioturbated in many places. This trend is consistent with deposition in first a shallow, then a deepening lake. Cores at sites 218, 219, 220 and 115 verify the clinoform seismic facies in South Basin as mud-buried littoral deposits on the lower flanks of the Pearson Reef moraine (see more detailed description and interpretation in Forbes et al., this volume). These former littoral sediments, together with the persistent occurrences of a coarse lithofacies in the basal part of the Winnipeg Sequence at offshore locations, and the recent drowning of marsh peat and forest trees (Nielsen, 1998) are evidence of coastal onlap and transgression within the basin.

Radiocarbon age of basal sediments

The age of the basal Lake Winnipeg sediments in most cores was obtained through a systematic search for dateable organic matter in 5-cm increments of sediment above the Agassiz Unconformity, or above the contact of basal mud or muddy sand over well sorted sand. Plant macrofossils were screened, selected and identified. After determining their paleoenvironmental significance, their age was determined by radiocarbon dating by accelerator mass spectrometry (AMS) (Telka, this volume; Appendix 10.6, this volume).

Ostracodes, where sufficiently abundant, were also cleaned, identified and submitted for AMS dating (Rodrigues, this volume; Telka, this volume; Appendix 10.6, this volume). Ostracode ages were mostly obtained in the basal muddy sands of the lower facies of the Winnipeg Sequence, but one date for the Upper Reflective Interval of the Agassiz Sequence was acquired (site 207). Elsewhere, mollusc shells were found and dated. The ages of these carbonate materials, shown in Figures 2 and 13, have been corrected for a regional hard-water effect by subtracting 255 years from their conventional radiocarbon ages. This value is based on the analysis of three shells of known age (between 1637 and 1912) from lakes Winnipeg and Winnipegosis and Dauphin Lake following procedures in Rea and Colman (1995) and Moore et al. (1998) (Table 5).

Radiocarbon ages from other lakes in North America were correlated to the Lake Winnipeg sediments using distinctive inclination features in the secular variation of the paleomagnetic field recorded in the sedimentary natural remnant magnetism (King et al., this volume). These were especially important for site 103 where no dateable organic matter was found.

Radiocarbon ages for basal mud are shown on the abbreviated core lithology plot (Fig. 2), listed in the core descriptions (Appendix 7.1, Todd et al., 1996 and Appendix 10.4, this volume), and described in detail by Telka (this volume). The basal ages in the North Basin between Warren Landing and Pigeon sills (Fig. 2) are generally consistent with a history of transgressive lake level pivoted on an outlet control at Warren Landing in the north. Basal ages are oldest nearest the outlet in the deepest part of the basin, an area that would have been inundated when the basin was in a more northerly downwarped state upon its isolation from Lake Agassiz. These are the cores from sites 103 to 202 with basal ages of 7.7 to 6.6 ka. Younger basal ages occur to the south and higher in the basin as at sites 201 (4.8 ka) and 209 (3.7 ka), again consistent with a transgressive lake history driven by glacial rebound.

In the central region between Pigeon and Hecla-Black sills (Fig. 2), basal ages are available at three cores only. This limited data set suggests a lengthy period of non-deposition until 4 ka following the isolation of the basin from Lake Agassiz about 8 ka. The younger 2.5 ka age for onset of sedimentation higher in the basin is consistent with transgression after 4 ka.

Many more ages were obtained in the South Basin with a pattern similar to that in the central region. The onset of sedimentation was delayed considerably until 4.1-3.9 ka in the deepest parts of the basin after isolation from Lake Agassiz, likely prior to 8 ka. A 5.4 ka *Scirpus* seed near the top of sand in core 224PC is abraded (Telka, this volume, Appendix 10.6) and thus has been transported and redeposited at a later date, possibly about 4 ka. Again, the basal ages for mud sedimentation higher in the basin are younger (e.g. 3.6 ka at 224, 3.3 ka at 217, and 2.9 ka at 219), and are indicative of rising lake level (transgression) after the onset of sediment accumulation in the deeper parts of the basin.

An uplift model for tilting of the Lake Winnipeg basin

Shorelines of various levels of glacial Lake Agassiz formed from 11.6 to <8 ka have been reconstructed by correlation of coastal sedimentary and geomorphic features through North Dakota, Minnesota, Manitoba, northwestern Ontario and part of Saskatchewan. The shorelines are deformed, all gently curving upward with increasing tilt to the north, indicating differential uplift and glacioisostatic recovery of Earth's crust from the load of the former Laurentide ice sheet. This evidence has been compiled and synthesized by Teller and Thorleifson (1983) as a strandline diagram showing traces of the former Lake Agassiz water surfaces in a section in the azimuth of maximum uplift, 034°. Isobases, indicating lines of equal uplift perpendicular to this azimuth, have been defined and numbered every 100 km north of the southern outlet of Lake Agassiz near the juncture of North Dakota, South Dakota and Minnesota (Fig. 10). Lake Winnipeg lies between isobases 5.6 and 8 which are 560 to 800 km N34°E of the southern Agassiz outlet.

Studies by Tackman et al. (1998) of tilted shorelines around Dauphin Lake and Lake Winnipegosis, and of gauged lake level trends in lakes Manitoba and Winnipeg, and Lake of the Woods have documented the continuation of glacioisostatic delevelling through the Holocene to the present. Tackman et al. (1998) found that the delevelling in a particular region can be represented by the exponential equation after Peltier (1994):

$$S = A(\exp(t/\tau)-1) \qquad (1)$$

where S = present slope or tilt of a shoreline which was once level at age t calendar years BP.

A = amplitude factor for uplift at a particular site, a parameter of expression (1).

τ = relaxation time for the uplift, a second parameter of expression (1).

The parameters of this equation were evaluated using all the tilt data for both Dauphin Lake and Lake Winnipegosis, and for the Burnside level of Lake Agassiz. The resulting expression for uplift (increasing slope) with age had a relaxation time of 6600 years and projected quite favourably back to the greater tilt of the older Upper Campbell level of Lake Agassiz (Tackman et al., 1998).

This type of equation was adapted in this study for quantifying and computing uplift within the Lake Winnipeg basin. Postglacial tilt data from Tackman et al. (1998) and glacial lake tilt data for the Burnside level of Lake Agassiz from Teller and Thorleifson (1983) were selected to evaluate its parameters. A basic assumption is that the relaxation parameter is constant throughout the modelled region. The amplitude parameter varies from place to place within the region depending on the magnitude of uplift, in this case by the slope of the Burnside level.

A variant of the uplift model was devised to compute changes in relative uplift (elevation) with time. As slope or tilt is the ratio of vertical distance (rise) to horizontal distance (run), we here define slope by the rise needed for the horizontal distance from a common point or isobase south of Lake Winnipeg measured along azimuth 034° to equal that slope. Isobase 5 was chosen as the common reference for computing relative uplift (elevation) in this study. The relaxation parameter, τ, is the same in the relative uplift mode as in the slope (tilt) mode, but the numerical value of the amplitude parameter, A', will differ from the slope version to accommodate uplift (elevation) values of the Burnside level above its elevation at Isobase 5. The equation for relative uplift (elevation), RU, is:

$$RU = A'(\exp(t/\tau)-1) \qquad (2)$$

Parameter evaluation and model testing

Because of the significant geographic separation between the Dauphin Lake tilt data (centred on Isobase 5.3) and the Lake Winnipegosis tilt data (centred on Isobase 6.3), the uplift model parameters were evaluated and tested separately for each data subset (Table 6). First the uplift model (1) was rearranged:

$$A(\exp(t/\tau)-1)-S = 0 \qquad (3)$$

For each set of known slope (S) and age (t) at a particular site (Table 6), equation (3) was evaluated for a series of estimated values of A and τ. The value obtained for equation (3) for each A and τ was expressed as a percentage of the known slope and termed a relative residual. The relative residuals were squared and summed until, by trial and error, a minimum relative residual was found for a particular pair of A and τ, the desired parameters for equation (3) at the site. This procedure provided an estimate for τ of 8050 years at Dauphin Lake and 3500 years at Lake Winnipegosis.

These two models were tested by computing separately the age for the diversion of the Saskatchewan River from Minago River channel (Isobase 7.8) over a former till barrier at Flying Post Rapids(Isobase 6.95) to northern Lake Winnipeg near Grand Rapids (Fig. 10). The actual age for the diversion is known (4.65 ka, 5320 Cal BP) from the age of a transition from river to swamp sediment in the abandoned Minago River channel (McMartin, this volume). The Minago channel was initially lower than the Flying Post barrier, but more rapid uplift raised the Minago channel until today it is 7 m higher than the former till barrier. By the time of the diversion (5320 Cal BP), the Winnipegosis-based model indicates the mean Saskatchewan River level was 2-3 m below the till barrier (Fig. 11). Likely the diversion occurred when the river was in flood, and it is quite possible that a 2-3 m river flood overtopped the till barrier to initiate the diversion at 5320 years ago. Thus the Winnipegosis model with a relaxation time of 3500 years is judged acceptable for application to the Lake Winnipeg basin. A similar condition is not reached for a further 2000 years with the model based on Dauphin Lake data. Consequently, the Dauphin model with a relaxation time of 8050 years was rejected for computing uplift in the Lake Winnipeg basin. The Winnipegosis model is in good agreement with the diversion information, given uncertainties in reconstructing the former river level in Minago channel (+2/-4 m) and in judging the elevation of the overtopped till barrier (±2 m) as estimated by I. McMartin (personal communication, 1999). The model is less successful in replicating older tilt data. For example, measured tilts of the Agassiz shorelines between Isobases 7 and 8 with estimated ages between 7.9 and 8.3 ka (McMartin, this volume) would only be replicated for a model with a shorter relaxation time (~3000 years), or if the tilt were 10 % less and age 12 % more for the Burnside reference level. However, the Winnipegosis model is retained as it is proven satisfactory for the younger Lake Winnipeg uplift.

Uplift history of sills

The principal sills which controlled overflowing lake levels in sub-basins of the Lake Winnipeg basin were identified by examination of lake bathymetric charts and Nelson River data (Lewis and Todd, 1996a). From south to north these are Hecla-Black Sill at a present depth of 9.5 m, Pigeon Sill at a present depth of 10 m, Warren Landing Sill at a present depth of about 4 m, and Jenpeg, a natural constriction with a controlling water level 1 m below the mean level of Lake Winnipeg before hydro-electric dam construction in 1976 (called Whisky Jack Narrows in Lewis and Todd, 1996a) (Fig. 10). The exponential uplift model with a relaxation time of 3500 years was applied to track the elevation of these key points with time. These calculations and those for the model test above involve:

1) estimation of the Burnside slope and change in relative uplift (elevation) of the Burnside level of Lake Agassiz relative to its elevation at Isobase 5 (Table 7);
2) computation of the amplitude parameter A' for each sill or other point (isobase) of interest using the relative uplift for the Burnside level (Table 8) as:
   $A' = RU/(\exp(9500/3500)-1)$
   by rearranging equation (2);
3) computation of the elevations, RE_t of points (isobases) of interest relative to the present mean level of Lake Winnipeg at 500 year intervals (Table 8) as:
   $RE_t = RE_p - RU$ or
   $RE_t = RE_p - A'(\exp(t/3500)-1)$
   where RE_p is the present elevation of the point of interest relative to the mean level of Lake Winnipeg which is set to 0. For example, the RE_p of Warren Landing Sill (see below) is -4 m.

Changes in the relative elevation of the sills are readily seen in the plots of Figure 12. Initially, after isolation from Lake Agassiz about 8500 cal BP, the Lake Winnipeg basin between Isobases 5.6 and 8.0 was downtilted about 65 m (Table 8). Independent water bodies were likely impounded in sub-basins behind their sills with overflow drainage cascading downward to the north from southern to central to northern basins, then to the Nelson River over the Warren Landing Sill. As time passed (Fig. 12), the more-rapidly uplifting northern sills overtook the southern sills. The early control for the northern basin, Warren Landing Sill, overtook the Pigeon Sill, control for the central Narrows area, about 4000 calendar years ago. Warren Landing Sill was submerged shortly after (about 3600 years ago) by the most northern

(Jenpeg) control. Finally, Jenpeg overtook Hecla-Black Sill and the southern basin about 3060 years ago (2.9 ka). After this time, all sub-basins were inundated and transgression was driven throughout the whole of Lake Winnipeg by the Jenpeg control, as at present.

Reconstruction of former lakes in Lake Winnipeg basin

Reconstruction of former lakes in the sub-basins of Lake Winnipeg was accomplished by approximating the lake surface with tilted planes, the larger the tilt, the older the reconstruction (Matile et al., this volume). Using a geographic information system (GIS), Matile et al. caused each plane to rest on the relevant sub-basin outlet sills. The GIS then defined the approximate shoreline by mapping the intersection of the plane with the bathymetry of the early Lake Winnipeg basin. The water surface area enclosed by the shoreline of each reconstruction was measured and reported by the GIS (Table 9). These areas are tied to the outlet sill elevations of the sub-basins, and thus, are measures of water surface area for potential overflowing (open) lakes.

The ages of the various tilted planes used in the lake area reconstructions were determined by matching their tilts to the slopes of the exponential uplift model at Isobase 6.95 for different ages. This isobase was chosen by trial and error to make the deviations between exponential and planar models of the water surfaces more or less equal at opposite ends of the lake (Table 9).

Lake Winnipeg, a result of uplift-driven transgression?

Here, the working hypothesis that lake evolution resulted from transgression due to postglacial differential uplift (tilting) is tested. A diagram was constructed to show the relation of all evidence of core lithology and sediment age to former water surfaces reconstructed according to the uplift model. First, all the core data of Figure 2 were projected onto the plane of maximum Agassiz tilt (N34°E) as shown in Figure 13. Then, computed lake surfaces were superimposed on Figure 13 for 6 time slices reconstructed by the exponential uplift model. The ages of these reconstructions are identical with those of a linear tilt model by Matile et al. (this volume) which approximate the exponential model and facilitate estimation of lake areas for each reconstructed phase (Table 9). The water surfaces within each sub-basin are controlled by (pivot on) the lowest available outlet sill, as the lakes are assumed to be always overflowing. After 2.9 ka (3060 cal BP), the various basin water levels coalesce and are controlled by a single outlet at Jenpeg, 62 km north of Warren Landing in the direction of Agassiz uptilt (N34°E) (Lewis and Todd, 1996a). The coalesced mode is illustrated by the 2.4 ka water surface and the present lake surface.

The computed water surface history in the northern basin south of the Warren Landing Sill is generally consistent with data in the cores. Cores in the north part (site 103 and northward) all plot below the earliest computed lake level, so subaerial exposure is not inferred. This is consistent with the absence of a desiccation zone on the Agassiz sediment surface in these cores (Fig. 9). The Agassiz surface at site 207 and those farther south all show dry crumbly texture (Appendix 10.4, this volume) often with enhanced magnetic susceptibility, bulk density and strength (Jarret, this volume), indicating desiccation, consistent with a period of subaerial exposure and pedogenesis as found in nearby Lake Manitoba by Teller and Last (1981; 1982). The surface zone of the Agassiz sediment at site 107 has some aspects of the same attributes and probably represents a zone of limited subaerial exposure and desiccation. These sediment properties are generally consistent with the uplift model, as Site 107 lies just above the earliest modelled lake surface (7.5 ka, Fig. 13) and all other sites farther south in the northern basin lie above the 6.7 ka or close to the 5.9 ka modelled lake surfaces. However, the basal ages at sites 201 and 209 are much younger (4.5 and 3.7 ka), suggesting an unexplained delay of several hundred years at least in the onset of Lake Winnipeg sedimentation.

There is a possibility that the onset of mud sedimentation was delayed earlier for about 1000 years in the deeper part of the northern basin because the basal ages for Lake Winnipeg sediment range from 7.7 to 6.6 ka. The older age is consistent with the modelled low-level lake at 7.5 ka (Fig. 13). However, the delay in mud accumulation at some of these sites suggests the low-level conditions persisted for almost 1000 years, or that the lowest levels occurred intermittently up to 1000 years after the basin was isolated from Lake Agassiz. A third possibility is that the lake levels declined about 6.6 ka, about 1000 years after the inception of Lake Winnipeg. The resulting erosion implied by these possibilities would have created a lag concentrate of redeposited coarser particles bearing ages of 7.7-6.6 ka, similar to that observed in the cores. This aspect of the lake history, either a prolonged suppression of lake rise, or intermittent declines and rises in lake level, or a decline about 6.6 ka, are not consistent with a model of open lake transgression driven by ongoing differential uplift.

Though the data are more limited in the central area between the Pigeon and Hecla-Black sills, the uplift-modelled age for inundation of site 215, between 4.8 and 3.5 ka, in the southern sector of the central area between the Pigeon and Hecla-Black sills compares well with its basal age of 3.6 ka. However, the uplift model suggests site 214 was inundated by 6.7 ka and submerged 2-2.5 m by 5.9 ka, yet onset of sedimentation was delayed until 3.6 ka. This early delay is not consistent with an open lake in the central basin evolving only by uplift-driven transgression.

For the southern basin, south of Hecla-Black Sill, deviation of the lake history from that of the uplift model is even more pronounced. The deepest Agassiz surfaces in the northern core sites (221, 222) are modelled to have been inundated by 7.5 ka and submerged 3-4 m by 5.9 ka, yet, the onset of postglacial sedimentation did not begin until after 4.7 ka, closer to 4.1 ka. The apparent delay in sedimentation occurred farther south also; at site 122/223 where inundation is indicated by 5.9 ka and submergence to 2.5 m by 4.8 ka, sedimentation begins only about 4.0 ka. Only at the southernmost site (224) is the onset of mud accumulation (3.6 ka) nearly coeval with the modelled age of submergence to 2.5 m (3.5 ka). Overall, the basal sediment age evidence indicates that mud accumulation in southern Lake Winnipeg was widely suppressed until about 4 ka, independent of ongoing uplift-driven transgression prior to that time.

A dry crumbly zone with enhanced physical properties as documented in areas of the northern basin that were subaerially exposed was also observed on the Agassiz surface at sites within the southern basin (e.g. 119, 120, 121, 122, 221, 222 and 223) (Fig. 9). The basin-wide delay in sedimentation, and the presence of dry-textured clay, indicating subaerial exposure and desiccation of the Agassiz deposits deep in the basin, suggest, not only a closed lake, but the complete absence of a perennial lake in the southern basin until about 4 ka BP. Because early to mid-Holocene climate is known to have been warmer and drier than present on the Interior Plains and adjacent Precambrian Shield (Bartlein et al., 1984; Winkler at al., 1986; Vance et al., 1995; Laird et al., 1996; Lemmen et al., 1997), we postulate that a dry climate induced dry lake conditions in the southern basin between about 8 and 4 ka. After 4 ka, as the climate became moister, the southern basin supported a perennial, overflowing lake whose levels were controlled by Hecla-Black Sill until the northern basin waters transgressed southward by ongoing differential uplift and coalesced with the southern basin lake. Inflow to the southern basin would have also been enhanced by channel avulsion and diversion of the Assiniboine River drainage from Lake Manitoba and the northern basin to the Red River and the southern basin at 4 ka (Rannie et al., 1989; Rannie, 1990; Nielsen et al., 1996; Curry, 1997) or later, close to 2 ka (Last et al., 1994). The ongoing uplift control caused relative water level to rise within the basin, and to force the long-term inundation and transgression evident in the offshore sediments and coastal zone after 4 ka. This postulate is consistent with a global evaluation of lake-level change and regional moisture balance between 6 ka and the present by Qin et al. (1998), who found that lakes in North America at the latitudes of southern Canada were "much drier than present" by two out of 5 lake status classes for lake level change world-wide.

The early lakes in the northern sub-basins, impounded behind the Pigeon and Warren Landing sills, appear to have been affected in a similar way as the southern basin, but to a lesser degree. Early Lake Winnipeg sedimentation at core sites in the central area began about 4 ka. At sites in the deeper, early inundated parts of the northern basin, coarser-grained sedimentation started nearly simultaneously with isolation of the basin from Lake Agassiz about 7.7 ka with silty clay mud and silt deposition continuing to about 6.4 ka at site 204PC (Lewis et al., Appendix 10.4, this volume). We postulate that a drier early Holocene climate induced closed-lake and shallower water conditions, perhaps intermittently, which caused widespread erosion, final formation of the Agassiz Unconformity in the offshore basin, and higher sedimentation rates prior to 6.5 ka as determined by King et al. (this volume). These climatic effects were superimposed on the continuing trend of basin deepening resulting from ongoing differential uplift. Closed-lake conditions continued until about 4.7 ka, when Saskatchewan River was diverted to North Basin (McMartin, this volume). Water supply to the lake was increased, possibly a result of river diversion and climate change, so occurrences of closed lake conditions were replaced by an open, overflowing lake after 4.7 ka. Then, southward inundation and transgression of the northern lake continued under the influence of differential rebound of the outlet, first at Warren Landing Sill, then at Jenpeg as described earlier.

Mid-Holocene climate effects on Lake Winnipeg

Vegetation history and climate change

An exploration of the potential for the warmer and drier mid-Holocene climate to reduce lake levels to closed conditions in the Lake Winnipeg sub-basins can be made using evidence from vegetation history for climate change and values of modern analogue climate parameters for precipitation, evaporation and runoff to assess change in water balance conditions. A review of paleo-pollen assemblages and synthesis of vegetation history for the Lake Winnipeg catchment area (Anderson and Vance, this volume) places the southern basin of Lake Winnipeg in grassland at 6.5 ka. The forested northern basin was near the grassland border.

The grassland vegetation zone is limited today to southeastern Alberta and southwestern Saskatchewan. A simple space-for-time approach is used in this preliminary exploration. We apply variations of the modern grassland climate parameters as examples for computing mid-Holocene water-balance values of the Lake Winnipeg sub-basins.

The critical determination is whether the grassland climate could have caused the lake to operate under closed conditions rather than overflowing conditions. Under closed conditions the steady-state water level is mainly determined (neglecting any groundwater loss or gain) by the balance of water inflow (land runoff and precipitation on the lake) and water loss by evaporation. With an increase in aridity, evaporation increases over the whole lake area, drawing down the lake level and reducing its surface area until evaporative water loss comes into balance with available inflow.

Climate-supportable lake area

The algebraic relationship for defining the critical or maximum lake area, that is the area supportable by the net balance of water supply and evaporation for a given climate and drainage basin, has been formulated by Bengtsson and Malm (1997) and L. Bengtsson (personal communication, 1999). These authors use the hydrological part of a conventional rainfall-runoff model with a lake routing procedure for computing lake levels and lake outflow. Starting with the water balance of a lake as

$$Q_{in} - Q_{out} + (p - e_p)A = A(\mathrm{d}h/\mathrm{d}t) \qquad (4)$$

where Q_{in} and Q_{out} are inflow and outflow respectively, p and e_p are precipitation and potential or lake evaporation respectively, A is lake surface area, h is lake surface level, and t is time.

When the lake level is just below the outlet sill, outflow will cease and the lake is in a closed state. Then $Q_{out} = 0$. If the lake level is also in an equilibrium (steady state) condition, then $\mathrm{d}h/\mathrm{d}t = 0$. Redefining Q_{in} as $q(A_b - A)$ where A_b is the total area of the drainage basin including its lake area, and q is the specific runoff in mm/year, equation (4) becomes

$$q(A_b - A) + (p - e_p)A = 0$$

or, rearranged,

$$A = A_b \cdot q/(q + e_p - p) \qquad (5)$$

Under these special conditions, the lake area A is the maximum water surface area that can be supported by a climate with mean annual parameters of q, e_p and p operating on the drainage basin of total area A_b which includes the lake area.

In applying equation (5) to Lake Winnipeg, it is assumed that groundwater inflow and outflow are negligible relative to surface flows and evaporation. Negligible groundwater flow is a reasonable assumption given the results of pore water analysis for three cores in this study (Betcher and Buhay, 1996; Buhay, 1996). The pore water carries an evaporative isotopic signature, more like entrapped lake water than inflowing groundwater. The relatively thick fine-grained sediments of Lake Agassiz in the Lake Winnipeg basin probably retard or localize groundwater inflow.

Criterion for open or closed lake status

The criterion for determining whether a basin is in open or closed status depends on the relative value of the potential surface area of a lake in that basin at the level of its outlet sill (open-lake area) and the maximum climate-supportable lake area, A, as determined from equation (5) above. If A is less than the open-lake area, the lake surface will not reach the outlet level of the basin and it will be in a closed state. On the other hand, if A is greater than the open-lake capacity of the basin, there will be surplus water available which will completely fill the basin and overflow its outlet; the lake is then in an open state. In cases where an upstream lake exists and is supplied by the same drainage basin as a downstream lake, the climate lake area A will apply to both lakes and must exceed their combined open-lake area for both lakes to be in an open state. This situation arises for the northern basin in which the large upstream lakes are Lakes Manitoba and Winnipegosis as well as the southern and central sub-basins of Lake Winnipeg during the mid-Holocene.

The open-lake areas for the sub-basins of Lake Winnipeg increased with time as a result of ongoing differential uplift. The open-lake areas have been evaluated for 6 times between 7.5 and 2.5 ka by Matile et al. (this volume) and are listed in Table 9. Climate-supportable lake areas for the same 6 times were evaluated by a consideration of drainage basin areas and river diversions under the influence of various exploratory analogue climates.

The component drainage basin areas for the northern and southern sub-basins of Lake Winnipeg from 7.5 ka to the present are listed in Table 10 with comments describing sources of the data. Note that the Saskatchewan River inflow begins about 4.7 ka (McMartin, this volume). The Assiniboine River switched twice between the northern and southern sub-basins. Prior to 7.5 ka it is thought to have discharged to the Red River and the southern basin (Nielsen et al, 1996) before switching to Lake Manitoba and the northern basin. This routing held until about 4 ka (Rannie et al., 1989; Nielsen et al, 1996; Curry, 1997) before the Assiniboine River switched back to the Red River as at present. Last et al. (1994) interpret a later date, about 2 ka, for this switch according to oxygen isotope data in the sediments of Lake Manitoba.

Analogue climates and lake status

Because the Lake Winnipeg basin straddled the vegetation boundary between grassland and boreal forest in the mid-Holocene (Anderson and Vance, this volume, Figure 3), two analogue climates were selected. Modern climate parameters from the National Hydrological Atlas (1978) for the Saskatoon area (Anderson and Vance, this volume, Figure 3) were selected as an analogue for a Grassland Border climate that possibly applied to the northern basin in the mid-Holocene. A drier climate for the Medicine Hat area (Anderson and Vance, this volume, Figure 3) was selected in a similar fashion as an analogue for a mid-Holocene Central Grassland climate that might have applied to the southern basin. The selected mean annual values of runoff, potential evaporation and precipitation are listed in Table 11 along with an estimated modern average climate for the Lake Winnipeg basin and a drier version of the Central Grassland climate.

Evaluations of lake status (open or closed) are provided for the Manitoba-Winnipegosis basin and the central sub-basin of Lake Winnipeg in Tables 12 and 13. Both were upstream lakes for the northern basin prior to the mid- to late Holocene. The total open-lake area for Lakes Manitoba and Winnipegosis and Dauphin Lake is assumed to have been relatively constant through the modelled period. This is because the two largest lakes, Manitoba and Winnipegosis drain through opposed outlets with respect to postglacial tilting. Thus, the area of Lake Manitoba which drains to the north increases with time, while the area of Lake Winnipegosis which drains south decreases with time.

Similarly, lakes in the central sub-basin (Table 13) are deemed closed or open by comparing their climate-supportable areas at different times with their computed potential open-lake areas (Table 9). In this case drainage is to the north and the open-lake areas progressively increase with time due to ongoing differential uplift.

Southern basin lake status

The evaluation of climate-supportable lake areas for the southern basin is laid out in Table 14 for modelled times from 7.5 ka to 2.9 ka when the northern and southern basins merged. On the left side of Table 14 areas of the component drainage basins are summed. On the right side climate-supportable lake areas are computed using equation (5) for selected analogue climates. The climate-supportable areas are plotted versus age on the same coordinates as the computed southern basin open-lake areas from Table 9 (Fig. 14). These plots show that the Grassland Border climate is far too moist (climate-supported lake areas too large) to account for the closed and desiccated southern basin during the mid-Holocene. The Central Grassland climate is closer to explaining the observations of desiccation but its lake area is still somewhat larger than the computed open-lake areas. A drier version of this climate with reduced runoff can account for the observed desiccated conditions because its small maximum lake areas are substantially less than the open lake areas. It is quite possible that dry conditions obtained in the southern basin while a climate like the Central Grassland climate operated in the extensive Red River and Winnipeg River drainage basins. It is well known that runoff is nonlinear with respect to precipitation in dry climates (Bengtsson and Malm, 1997). Precipitation on these large catchments was likely evaporated quickly, especially if most precipitation fell as summer rain, thereby denying runoff to the downstream receiving basin. Evaporation from the many upstream lakes in the Winnipeg River basin would also reduce downstream runoff. The Central Grassland analogue is the driest climate that can be considered for the region in relation to the well documented reconstructed Holocene climate at Elk Lake (Anderson and Vance, this volume, Figure 3). This site in Minnesota is at the border of prairie southeast of Lake Winnipeg. During the driest parts of the Holocene the precipitation values of the Central Grassland climate fall in the lowest part of the range of reconstructed precipitation values at Elk Lake (Bartlein and Whitlock, 1993).

The black dashed line in Figure 14 is a generalized indication of the probable trends in water supply that affected the southern basin as a result of climate change and river diversions. From about 7.5 to 5.4 ka water deficits were most severe, following the suppressed runoff version of the Central Grassland climate. An abraded *Scirpus* seed was dated 5.4 ka and this might indicate the presence of seasonal ponds. The postulated trend then begins to rise to 4 ka when it rises abruptly with the coincident diversion of the Assiniboine River and the onset of wetter and cooler climate evidenced by the appearance of widespread Lake Winnipeg sedimentation. This brings the basin into open status and overflow begins toward the central and northern basins. From this time forward the water supply is inferred to rise towards the relatively moist conditions of the present, keeping the basin open until it merges with the northern basin about 2.9 ka.

The trend to cooler temperatures after 4 ka in the southern basin is reflected in the pore water data in core 115 (Betcher and Buhay, 1996) which show an upward gradient toward lighter $\delta^{18}O$ composition. The rise of supportable lake areas with wetter climate would intersect the predicted lake area curve at 4 ka and convert the South Basin water body from a closed state to an increasingly open and overflowing state. This rise probably fluctuated with variations in late Holocene climatic aridity and water supply, but we make no attempt here to identify or synthesize these changes. A possible example of water level fluctuation is the unconformity dated 3340 BP in core 217PC in the northern part of the southern basin on the Hecla-Black Sill (Appendix 10.4). The implied hiatus was probably less than 100 years as it could not be resolved by AMS age determinations above and below the unconformity. Overall, the lakes in the southern basin were dominantly controlled by climate before 4 ka (while rebound continued) and by differential rebound resulting in southward transgression after 4 ka.

Northern basin lake status

The evaluation of lake area for the northern basin requires consideration of all the Lake Winnipeg component basins and is considerably more complex. The procedure is laid out for the modelled periods in Table 15; Tables 15a and 15b should be considered in parallel as though they were placed side-by-side.

In Table 15a the areas of the contributing drainage basins are summed. Non-contributing basins, indicated by a zero area, arise because a river has not yet been diverted (e.g. Saskatchewan River until 4.7 ka) or because the basins drain to an upstream lake which is closed (e.g. the southern basin from 7.5 to 4 ka) and contributes no runoff to the northern basin. In Table 15b the summed areas of contributing drainage basins for each modelled period are computed into climate-supportable lake areas for the designated analogue grassland climates using equation (5). These climates are distributed into the component basins consistent with the geological observations of closed or open conditions in the southern basin.

The supportable lake areas for the Grassland Border and Central Grassland analogue climates are plotted against age in Figure 15 (coloured dashed lines). As for Figure 14, the computed potential open-lake areas are also plotted (black line and dots). The lake areas for the Central Grassland climate fall well below the computed surface areas, suggesting the lakes would be in a severely closed state throughout their early history. As this is contrary to the observed sedimentary record, we consider the Grassland Border climate as a more probable example for the mid-Holocene climate of the northern basin. In this case, the lake would tend gently toward a closed state after 7.5 ka but become more severely closed between about 6.5 and 4.7 ka when the onset of inflow of Saskatchewan River would have brought the lake into an open, overflowing state (Fig. 15). This history conforms much better with the interpretations made in this report that initially, an early, shallow, open lake existed, controlled by the Warren Landing Sill. This water body locally eroded and winnowed the underlying Agassiz sediments to produce, in part, the Agassiz Unconformity and coarser deposits of sand or interbedded sand and mud at the base of the Winnipeg Sequence. A drop in lake level about 7.0-6.6 ka caused more widespread winnowing and erosion. The Grassland Border climate scenario is consistent with this record. A climate-induced lowstand about 7.0-6.6 ka is particularly consistent with the occurrence of high sedimentation rates prior to 6.5 ka as found by King et al. (this volume).

The foregoing scenario suggests a more severely closed state after 6.5 ka until 4.7 ka, a condition already inferred by Buhay (1996) from geochemical observations. These observations showed that $\delta^{18}O$ isotope ratios for lake surface waters on phytoplankton remains (cellulose) were greatly enriched (e.g. by evaporation) for a long period relative to bottom (pore) waters from 520 to 380 cm in core 103. This interval is the same period of predicted lake closure in Figure 15, as determined by paleomagnetic correlation of radiocarbon ages to core 103 (King et al., this volume). The switch from closed to open lake status, coincident with the diversion of the Saskatchewan River at 4.7 ka is also supported by geochemical observations in core 103. Above

380 cm depth or < 4.7 ka, Buhay (1996) found that the $\delta^{13}C$ isotope ratios in bulk organics and cellulose began to diverge for the rest of the Holocene. The bulk organics became more and more depleted, consistent with an interpretation that more and more terrestrial organic carbon ($\delta^{13}C$ about -25 to -28) was being carried into the lake where it diluted the influence of lacustrine phytoplankton production ($\delta^{13}C$ about -20 to -24).

Given the above support, we postulate a simple generalized climate history (dashed black curve in Fig. 15) for the northern basin, starting with an equivalent of the Grassland Border climate and continuing to about 4 ka. (The offset at 4.7 ka indicating a significant increase in water supply to the basin was entirely due to diversion of the Saskatchewan River.) At 4 ka the postulated climate becomes wetter and cooler, rising to the present average climate which would support a lake area of 460,900 km^2 (Table 15b and Fig. 15). This rise probably fluctuated with variations in late Holocene climatic aridity and water supply, perhaps indicated by fluctuations in the isotopic composition of the sedimentary organic matter in core 103 (Buhay, 1996). We make no attempt here to identify or synthesize these changes.

The change to cooler conditions after 4 ka is reflected in the geochemical pore water data of Betcher and Buhay (1996) by an upward gradient toward lighter $\delta^{18}O$ in core 103. The postulated rise in climatic moisture and runoff would maintain an open lake status in the northern basin after 4.7 ka. Thus, lake levels in the northern basin were dominantly controlled by differential rebound of an open, overflowing lake throughout most of the basin history, except for a relatively short period from 6.5 to 4.7 ka when the steady-state lake was likely in a closed condition and climatic control dominated while rebound continued.

SUMMARY

- A total of 33 cores recovered sediments from two major seismic units, the Agassiz and Winnipeg Sequences which largely fill the Lake Winnipeg basin.

- Core quality varied considerably. The quality of mud recovery was evaluated by comparing recovered sediment intervals with thicknesses determined by acoustic and seismic reflection methods. Shortfalls in mud recovery by coring with 9-m long barrels ranged from zero to under 2 m most commonly, and to one extreme value of 3.4 m. The acoustic/seismic technique is favoured for determining the depth or elevation of the Agassiz Unconformity where seismic velocity has been measured in the sediment cores.

- Till is absent or so thin (e.g. <1 m approximately) beneath much of the lake area that it cannot be resolved in seismic reflection profiles.

- Distinctive packages of coherent, strong reflections in Seistec records (2-6 kHz) give character to the Agassiz Sequence, allowing its subdivision into reflective facies intervals. Reflections show that the glaciolacustrine sediments conformably drape the underlying relief on bedrock or morainic surfaces. By comparison with core lithologies, physical properties and shore exposures, the coherent reflection facies is correlated to zones of silty clay rhythmites or laminated silty clay containing millimetre-scale silt laminae. Aggregate thicknesses of these sediments create layers greater than 20 cm thick with differing acoustic impedance, the product of sound velocity and bulk density. The boundaries between layers of differing impedance are the likely sources of the strong, coherent reflections. Within the Agassiz Sequence, these zones, with their visibly more numerous silt laminae, are thought to mainly reflect glaciolacustrine deposition nearer an ice margin (the inferred sediment source) than sediments which produce a transparent seismic facies. The uppermost strong coherent reflection package (e.g. in North Basin) correlates to interbedded sandy silt and clay and may originate by wave and current winnowing in an environment of declining lake depth.

- Disturbance of the Agassiz Sequence south of Long Point (The Pas moraine) suggests an episode of loading of Lake Agassiz sediment, possibly by a surge of a thin ice margin.

- The regional Agassiz Unconformity, which truncates reflections and facies in the underlying Agassiz Sequence, is remarkably smooth and planar. It is thought to have formed dominantly by successive episodes of wave abrasion in relatively shallow water during the late falling-water phases of glacial Lake Agassiz, the postglacial early phases and closed-lake lowstands, and in the postglacial and modern shorefaces of Lake Winnipeg.

- The basal reflections within the Winnipeg Sequence provide abundant evidence of onlap. This, combined with observations of coarser basal sediments in cores and evidence of coastal onlap indicates the Winnipeg sediments were deposited in a transgressive lake with increasing water level.

- Basal radiocarbon ages for the Winnipeg Sequence show that the onset of sedimentation in North Basin began with the predicted isolation from Lake Agassiz about 7.7 ka, but sedimentation was suppressed at southern sites in North Basin and in the South Basin until 5-4 ka. The delay in sediment accumulation is contrary to the predictions of lake evolution based on differential postglacial rebound alone, which assume that lakes are always open and overflowing at their outlets.

- Water balance computations suggest that the early history of Lake Winnipeg was influenced by closed lake conditions induced by warmer and drier climates similar to modern climates in southeastern Alberta and southwestern Saskatchewan. Under such climates the southern basin appears to have dried up in the mid-Holocene. A lake returned and switched to open conditions after 4 ka in response to the onset of a cooler and wetter climate. A shorter and less intense episode of closed lake conditions is inferred for the northern basin. Diversions of the Saskatchewan River to the northern basin at about 4.7 ka, and the Assiniboine River to the Red River and the southern basin at about 4 ka are both coincident with the switch in lake status from closed to open.

- This study of Lake Winnipeg illustrates a general relationship between transgressive lake histories and climate. As the areas of open, overflowing lakes expand in a suitably dry climate, for example, by transgression in a postglacial rebounding basin, they may exceed the capacity of the drainage basin to supply water to offset increasing losses to evaporation. The water level is drawn down by evaporation to a smaller, new, steady-state area, and the lake becomes closed with a surface elevation below that of its outlet. Conversely, when climate becomes markedly wetter, water supply increases and evaporation decreases so the lake may rise to its outlet and switch to an open, overflowing state.

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Table 1. Core recovery ratio, Lake Winnipeg (LW) mud core length, and acoustic mud thickness in long cores of cruises 94-900 and 96-900

Site[1]	Long core recovery ratio[2]	LW mud thickness in core[3] (m)	LW acoustic mud thickness[4] (ms, two-way time)	LW mud acoustic velocity[5] (m/s)	LW acoustic mud thickness [6] (m)	Difference: acoustic mud thickness -core mud length[7] (m)
103	0.86	6.86	9.69	1405	6.81	-0.05
104	n.a.	n.a.	1.96	1405	1.38	n.a.
105	0.95	.645	.97	1405	0.68	0.04
106	0.94	1.82	2.65	1405	1.86	0.04
107	0.80	1.72	3.41	1405	2.40	0.68
110	n.a.	2.09	n.a.	n.a.	n.a.	n.a.
113	0.31	n.a.	12.5	1415	8.84	n.a.
115	0.73	2.68	6.76	1405	4.75	2.07
119	1.00	1.71	3.73	1410	2.63	0.92
120	n.a.	1.96	3.18	1410	2.24	0.28
121	0.59	4.75	8.68	1410	6.12	1.37
122	0.49	4.35	11.05	1410	7.79	3.44
201	0.88	4.39	7.5	1405	5.27	0.88
202	0.66	1.79	3.45	1405	2.42	0.63
203	0.65	n.a.	9.92	1405	6.97	n.a.
204	0.63	5.79	9.32	1405	6.55	0.76
205	0.61	1.07	2.14	1405	1.50	0.43
206	0.64	.69	2.35	1405	1.65	0.96

207	0.64	1.24	2.61	1405	1.83	0.59
208	0.54	1.16	3.62	1405	2.54	1.38
209	0.77	1.04	2.66	1405	1.87	0.83
213	0.95	.15	2.81	1410	1.98	1.83
214	0.95	3.75	5.65	1415	4.00	0.25
215	1.00	3.61	5.05	1415	3.57	-0.04
216	1.00	2.04	5.3	1410	3.74	1.70
217	0.97	3.02	3.97	1450	2.88	-0.14
218	0.46	.72	2.12	1405	1.49	0.77
219	1.00	1.65	3.21	1400	2.25	0.60
220	1.00	4.07	6.67	1405	4.69	0.62
221	0.82	5.22	9.22	1410	6.50	1.28
222	0.94	7.35	10.58	1415	7.49	0.14
223	0.88	6.87	11.05	1410	7.79	0.92
224	0.96	5.82	9.22	1420	6.55	0.73

1 Bold font = solid piston core; Underlined font = split piston core; Normal font = gravity core.

2 Recovery ratio = division of recovered long core length by apparent penetration of corer. Core length data for sites 103-122 are from Appendix 7.1 (Todd *et al.*, 1996), and apparent penetration data are from Table 9 (Todd, 1996). For sites 201-224, the core recovery ratio is taken from Table 7 in Todd, this volume.

3 from Appendix 10.4, this volume.

4 measured from Seistec high-resolution seismic profiles at long core sites.

5 average sound velocity for the mud section in the core or based on other cores in the area. selected from values in Appendix 10.3 by Jarrett (this volume).

6 calculated by multiplying (column 4)/2 by (column 5)/1000.

7 subtraction of column 3 from column 6.

n.a. not available: apparent penetration not observed or corer did not penetrate to Agassiz sediment so mud thickness could not be determined.

Table 2. Comparison of strong coherent reflection facies with core lithology and acoustic impedance in the Agassiz Sequence

Seismic Facies	Core[1]	Depth Interval[1] (cm)	Lithology[1]	ρ Bulk Density[2] (Mg/m^3) Layer 1 & 2	v Sound Velocity[2] (m/s) Layer1 & 2	Z = ρxv Acoustic Impedance Layer 1 & 2	R = (Z2-Z1)/(Z2+Z1) Reflection Coefficient
SRI coherent reflections South Basin	120PC	245-318	Thin mm-scale silty clay rhythmites with scattered silt laminations and dropstones below/above silty clay	1.65 (1) 260-300 cm 1.73 (2) 300-340 cm	1520 (1) 260-300 cm 1535 (2) 300-340 cm	2508 (1) 260-300 cm 2656 (2) 300-340 cm	0.029
HRI coherent reflections South Basin	119PC	220-321	Medium thick sub-cm silty clay rhythmites below banded silty clay, all with silt laminations	1.83 (1) 250-275 cm 1.90 (2) 300-340 cm	n.a. (1) n.a. (2)	n.a. (1) n.a. (2)	n.a.
LRI coherent reflections North Basin	105PC	350-510	Medium thick sub-cm silty clay rhythmites, gritty with silt partings and dropstone	1.65 (1) 1.75 (2) (2 zones 390-440 and 460-500 cm)	1460 (1) 1500 (2) (2 zones 390-440 and 460-500 cm)	2409 (1) 2625 (2) (2 zones 390-440 and 460-500 cm)	0.043
LRI coherent reflections North Basin	206PC	387-469	Medium thick sub-cm silty clay rhythmites, constituent gray layers thicker with silt laminae in places	1.75 (1) 1.85 (2) (2 zones within 405-440 cm)	n.a. n.a.	n.a. n.a.	n.a.
MRI coherent reflections North Basin	106PC	248-530	Thick cm-scale silty clay rhythmites with silt laminations	1.55 (1) (250-300 and 330-390 cm 1.75 (2) (300-330 and 390-430 cm)	1450 (1) (250-300 and 330-390 cm 1500 (2) (300-330 and 390-430 cm)	2248 (1) (250-300 and 330-390 cm 2625 (2) (300-330 and 390-430 cm)	0.077

MRI coherent reflections North Basin	103PC	686-816	Medium thick, increasing downward to thick cm-scale silty clay rhythmites	1.50 (1) (730-750 and 770-790 cm) 1.64 (2) (750-770 and 790-810 cm)	1430 (1) (730-750 and 770-790 cm) 1452 (2) (750-770 and 790-810 cm)	2145 (1) (730-750 and 770-790 cm) 2381 (2) (750-770 and 790-810 cm)	0.052
MRI coherent reflections North Basin	202PC	507-579	Thick cm silty clay rhythmites with gray laminated layers, likely silty	1.62 (1) <510 cm 1.71 (2) >510 cm	1440 (1) <510 cm 1470 (2) >510 cm	2333 (1) <510 cm 2480 (2) >510 cm	0.031
MRI coherent reflections North Basin	205PC	465-537	Thick silty clay rhythmites up to 7 cm with silt laminae in places	1.63 (1) 455-475 cm 1.75 (2) above and below (1)	1440 (1) 455-475 cm 1470 (2)	2298 (1) 455-475 cm 2573 (2)	0.056
MRI coherent reflections North Basin	206PC	69-134	Thick silty clay rhythmites up to 5 cm	1.62 (1) <120 cm 1.51 (2) >120 cm	1450 (1) <120 cm 1435 (2) >120 cm	2349 (1) <120 cm 2167 (2) >120 cm	-0.04
URI coherent reflections North Basin	207PC	160-334	Rhythmically laminated silty clay with silt layers	1.72 (1) 290-310 cm 1.64 (2) 310-325 cm	1450? (1) 1465? (2) 310-325 cm	2403? (1) 290-310 cm 2494 (2) 310-325 cm	-0.019
URI coherent reflections North Basin	208PC	116-244	Finely laminated silty clay with lenticular silt laminae, common 155-180 cm	1.69 (1) above 182 cm 1.73 (2) 182-198 cm	1480? (1) above 182 cm 1500?	2501? (1) above 182 cm 2595? (2) 182-198 cm	0.018
URI coherent reflections North Basin	205PC	107-410	Finely laminated silty clay with occasional silt laminations	Minor variations of 0.5	Minor variations of 15	n.a	n.a.

URI coherent reflections North Basin	107PC	194-696	Banded clay with sporadic thin silt lenses	1.59 (1) 593-613 cm 1.65 (2) 613-680 cm	1450 (1) 593-613 cm 1462 (2) 613-680 cm	2306 (1) 593-613 cm 2412 (2) 613-680 cm	0.022

[1] 100 series core logs in Appendix 7.1 (Todd et al., 1996); 200 series core logs in Appendix 10.4 (this volume).

[2] bulk density and sound velocity for 100 series cores in Appendix 7.2 (Todd et al., 1996); for 200 series cores in Appendix 10.3 (this volume. Values estimated visually from downcore plots.

n.a. not available, or cannot be calculated if listed under impedance or reflection coefficient.

Table 3. Water depth and depth to base of Lake Winnipeg (LW) mud for long core sites of Cruises 94-900 and 96-900 and depth/elevation of bathymetric sills, relative to mean lake level (217.4 m asl)

(1) Site	(2) Lake surface elevation[1] (m asl at time of survey)	(3) Lake surface above mean (m at time of survey)	(4) Observed water depth[2] (m)	(5) Water depth relative to mean lake level (m)	(6) LW acoustic mud thickness[3] (m)	(7) Depth to mud base below mean lake level[4,6] (m)	(8) Elevation of mud base above sea level[5,6] (m)
103	217.6	0.2	15.9	15.7	6.81	22.51	194.89
104	217.5	0.1	16.2	16.1	1.38	17.48	199.92
105	217.6	0.2	15.8	15.6	0.68	16.28	201.12
106	217.6	0.2	16.8	16.6	1.86	18.46	198.94
107	217.6	0.2	17.1	16.9	2.40	19.30	198.10
110	217.7	0.3	11.3	11.0	*2.10*[7]	*13.10*	*204.30*
113	217.7	0.3	9.8	9.5	8.84	18.34	199.06
115	217.8	0.4	10.7	10.3	4.75	15.05	202.35
119	217.7	0.3	9.8	9.5	2.63	12.13	205.27
120	217.8	0.4	10.1	9.7	2.24	11.94	205.46
121	217.8	0.4	10.4	10.0	6.12	16.12	201.28
122	217.8	0.4	9.8	9.4	7.79	17.19	200.21
201	217.8	0.4	13.0	12.6	5.27	17.87	199.53
202	217.8	0.4	13.6	13.2	2.42	15.62	201.78
203	217.8	0.4	16.5	16.1	6.97	23.07	194.33
204	217.8	0.4	15.9	15.5	6.55	22.05	195.35
205	217.8	0.4	15.9	15.5	1.50	17.00	200.40
206	217.8	0.4	15.9	15.5	1.65	17.15	200.25
207	217.7	0.3	17.1	16.8	1.83	18.63	198.77

208	217.7	0.3	15.6	15.3	2.54	17.84	199.56
209	217.7	0.3	16.5	16.2	1.87	18.07	199.33
212	217.8	0.4	11.0	10.6	5.29	15.89	201.51
213	217.8	0.4	11.5	11.1	1.98	13.08	204.32
214	217.8	0.4	11.3	10.9	4.00	14.90	202.50
215	218.1	0.7	11.6	10.9	3.57	14.47	202.93
216	218.1	0.7	11.9	11.2	3.74	14.94	202.46
217	218.1	0.7	11.1	10.4	2.88	13.28	204.12
218	217.8	0.4	10.4	10.0	1.49	11.49	205.91
219	217.8	0.4	10.5	10.1	2.25	12.35	205.05
220	217.8	0.4	10.5	10.1	4.69	14.79	202.61
221	217.9	0.5	10.4	9.9	6.50	16.40	201.00
222	217.9	0.5	10.4	9.9	7.49	17.39	200.01
223	217.6	0.2	9.75	9.55	7.79	17.34	200.06
224	217.9	0.5	8.5	8.0	6.55	14.55	202.85
H-B Sill	depth from marine chart			9.75	0.00	9.75	207.70
P Sill	depth from marine chart			10.0	0.00	10.00	207.40
WL Sill	depth from marine chart			5.5	0.00	5.50	211.90

1 obtained from water level gauge information for date of survey.

2 measured by echo sounder on CCGS *Namao* at time of coring.

3 measured and calculated from Seistec seismic profile through site as for Table 1.

4 calculated by summing columns 5 and 6.

5 calculated by subtracting column 7 from 217.4 m.

6 mud base overlies the Agassiz Unconformity and eroded Agassiz clay except at 204 where LW mud conformably overlies Agassiz clay, and at 115, 218, 219 and 220 which overly LW sand.

7 no seismic profile available, thickness is core measurement.

Table 4. Examples of observations of baselap in the Winnipeg Sequence			
Area	**Site[1] and (Depth m)**	**Observations on Seistec profile at site**	**Type of Baselap**
South Basin, Pearson Reef	115 (15.1)	Basal discontinuous reflections overlap upward sloping Agassiz Unconformity (AU)	Onlap
South Basin, Traverse Bay	119 (12.1)	Basal reflections overlap side of small depression in AU about 100 m SE of core site	Onlap
South Basin, Traverse Bay	120 (11.9)	Basal coherent reflections overlap AU, especially in small depression at NW side of profile	Onlap
South Basin, central	121 (16.1)	At small depression 200 m W of site basal reflections overlap the AU	Onlap
Northern South Basin	217 (13.3 AU and 11.6)	Infill reflections overlap margins of depression (channel?) in AU. Reflections also overlap higher unconformity	Onlap
South Basin, Pearson Reef	218(11.5), 219(12.4), 220(14.8)	Basal discontinuous reflections overlap upward sloping AU east of and beneath clinoform (paleobeach) facies	Onlap
Central	113 (18.3)	Basal reflections overlap towards SE against upward sloping AU about 50 m NW of 113 site	Onlap
Central	215 (14.5)	Basal reflections overlap towards S on upward sloping AU about 200 m N of 215 site	Onlap
North Basin, south of Berens Island	213 (13.1)	Basal reflections overlap to S against upward sloping AU	Onlap
North Basin, Berens to George Islands	209 (18.1)	Basal reflections overlap towards S on upsloping AU, vicinity of 209 site	Onlap
North Basin, N of Long Point	103 (22.5)	Basal low-amplitude reflections overlap on upward sloping AU from about 325 to 100 m NE of core site	Onlap
Northeastern North Basin	104 (17.5)	Basal reflections overlap AU at small depression 120 m NE of core site	Onlap
Northeastern North Basin	105 (16.3)	Basal reflections and transparent zone overlap upward sloping AU	Onlap
Northeastern North Basin	106 (18.5)	Basal reflections overlap in area of AU depression 150-300 m NE of core site	Onlap
North Basin, N of Long Point	204 (22.1)	Basal high-amplitude reflections overlap upward sloping AU 250-350 m NE of core site	Onlap

[1] 100 series sites in Appendix 7.1, Todd et al., 1996; 200 series sites in Appendix 10.4, this volume. Figure in parentheses is depth of unconformity (base of Winnipeg Sequence in most cases) in metres below modern mean lake level (217.4 m asl) from Table 3.

Table 5. Calculation of hard-water effect (hwe) for radiocarbon-dated mollusc carbonate shells in southern Manitoba[§]

Location and mollusc identification	Reference	Death date & true age before 1950 AD (years)	Conventional ^{14}C age & Lab. No.	$\Delta^{14}C$ ‰[*] & inert CO_2 correction (years)	Hard-water effect (hwe) (years)
Southeast Lake Winnipeg *Strophitus undulatus* (Say)	Nielsen et al., 1982	1941 -9	440±100 GSC 3281	-19.4 -155	-276±100
Northwest Lake Winnipegosis *Lampsilis radiata siliquoidea* (Barnes)	Nielsen et al., 1987	1012 -38	310±100 BGS 1099	-7.9 -60	-212±100
Dauphin Lake *Sphaerium*	Tackman et al., 1998	1637[#] -313[#]	590±60 Beta 68105	assumed 0 0	-277±90
Mean hard-water effect (years)					-255±100

[§] following Rea and Colman (1995) and Moore et al. (1998).

[*] from Table 1 in Stuiver and Quay (1981), average of estimated 3 years of shell growth.

[#] based on the calibrated calendar age before 1950 AD of charred wood found in conjunction with the *Sphaerium* sample. The conventional age of the wood is 300±90 BP (Beta 68102) (Tackman et al., 1998). Calibrated with the program Calib4.1.2 and the onboard atmospheric decadal data set (Stuiver and Reimer, 1993; Stuiver et al., 1998).

Table 6. Data table for calculation of an uplift model for the Lake Winnipeg area[1]

Shore	Age ^{14}C convntl years BP	Age ^{14}C+/- years	Hard-water effect years	Age ^{14}C corrected years BP	Age[2] Calendar years BP	Slope S cm/km	Slope+/- cm/km	Azimuth degrees	Azimuth+/- degrees
Lake Winnipegosis area, Isobase 6.3									
AgBnsde	8500	100	0	8500	9500	30.7		34	
Dawson	5290	30	-255	5035	5750	13.5	0.9	24.3	2.6
Wgs4	3330	40	-255	3075	3320	2.2	0.9	24.3	
Wgs3	1510	60	-255	1255	1180	1.3	0.4		
Wgs2	1080	40	-255	825	730	0.7	0.2		
Dauphin Lake area, Isobase 5.3									
AgBnsde	8500	100	0	8500	9500	25.31			
DpnIV	7910	50	-255	6095	6950	21.7	3.9	44.4	10.3
DpnId	4640	20	-255	4385	4940	8.8	1.3	53.4	7.5
DpnIa3	3020	30	-255	2765	2860	5.3	0.6	62.3	5

[1] Agassiz Burnside (AgBnsde) data from Thorleifson in Teller et al. (1996) and Teller & Thorleifson (1983). All other data from Tackman et al. (1998).

[2] Calibrated with the Calib412 program with its 1998 atmospheric data set (Stuiver and Reimer, 1993).

Table 7. Estimating equations for Agassiz Burnside slope and relative uplift (elevation above that at Isobase 5)

Agassiz Burnside shoreline data (Teller & Thorleifson 1983)				Burnside slope and relative uplift (elevation above that at Isobase 5) estimated for any isobase expressed as a decimal number		
Isobase	Dist N	Slope	Elevation	Isobase	Slope	Elevation
	Iso5 km	cm/km	m asl		cm/km	aboveIso5
5	0	24.56	272.47	5	24.6285	0.2262
6	100	28.79	299.48	6	28.5845	26.3302
7	200	37.11	332.53	6.38	31.339785	38.427291
8	300	50.89	376.15	7.07	38.105494	63.458852
				8	50.8215	103.4532
				8.62	61.593225	134.10665

Best fitted equation for slope of Burnside (Y) vs distance north of isobase 5 (X) is:
Y=0.00023875*Xsquared+0.015685*X+24.6285 (fitted in GRAPHER)
Rsquared for degree 1 = 0.94334; Rsquared for degree 2 = 0.999768

Best fitted equation for elevation above Burnside at Isobase 5 (Y) vs distance north of isobase 5 X is: Y=0.00041525*Xsquared+0.219515*X+0.2262 (fitted in GRAPHER)
Rsquared for degree 1 = 0.9883; Rsquared for degree 2 = 0.999829

Table 8. Calculation of site elevation (m) relative to present mean lake level as a function of age *t*

Site				H-B Sill	Pig'n Sill	WL Sill	Jenpeg[1]
Isobase	Iso 5	Iso 5.6	Iso 6	Iso 6.38	Iso 7.07	Iso 8	Iso 8.62
REp	0	0	0	-9.5	-10	-4	-1
Distance	0	60	100	138	207	300	362
AgB RU	0.2265	14.8923	26.3305	38.427591	63.459152	103.4535	134.106951
A'	0.016071	1.0566543	1.8682295	2.7265552	4.502621	7.3403424	9.51529849
Age t years Cal BP	Elevation at t	Elevation at t	Elevation at t	Elevation at t	Elevation at t	Elevation at t	Elevation at t
0	0	0.00	0	-9.5	-10	-4	-1
500	0.00	-0.16	-0.29	-9.92	-10.69	-5.13	-2.46
1000	-0.01	-0.35	-0.62	-10.40	-11.49	-6.43	-4.15
1500	-0.01	-0.57	-1.00	-10.96	-12.41	-7.93	-6.09
2000	-0.01	-0.81	-1.44	-11.60	-13.47	-9.66	-8.33
2500	-0.02	-1.10	-1.95	-12.34	-14.70	-11.65	-10.92
3000	-0.02	-1.43	-2.53	-13.20	-16.11	-13.96	-13.91
3500	-0.03	-1.82	-3.21	-14.19	-17.74	-16.61	-17.35
4000	-0.03	-2.26	-3.99	-15.32	-19.62	-19.68	-21.32
4500	-0.04	-2.77	-4.89	-16.64	-21.78	-23.21	-25.90
5000	-0.05	-3.35	-5.93	-18.15	-24.29	-27.29	-31.19
5500	-0.06	-4.03	-7.12	-19.90	-27.17	-31.99	-37.29
6000	-0.07	-4.81	-8.51	-21.91	-30.50	-37.42	-44.32
6500	-0.09	-5.71	-10.10	-24.24	-34.34	-43.68	-52.43
7000	-0.10	-6.75	-11.94	-26.92	-38.77	-50.90	-61.79
7500	-0.12	-7.95	-14.06	-30.01	-43.88	-59.23	-72.59
8000	-0.14	-9.33	-16.50	-33.58	-49.77	-68.84	-85.05
8500	-0.17	-10.93	-19.32	-37.70	-56.57	-79.92	-99.41
9000	-0.19	-12.77	-22.58	-42.45	-64.41	-92.70	-115.99

[1] Mean water level (1 m below mean lake level) at the natural constriction before dam construction in 1976. For relative mean lake level upstream, add 1 m to the elevations below

REp = Present elevation of site relative to mean lake level

RU = Uplift relative to elevation of Agassiz Burnside level at Isobase 5, computed as in Table 7

Amplitude parameter *A'* = RU(Row 5)/(exp(9500/3500)-1)

Site elevation at age t years relative to lake level = REp(Row3)-A'(Row6)*(exp(*t*/3500)-1) where *t* is in first column

Table 9. Lake reconstructions, age and computed open-lake areas

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9
Slope cm/km	**Age Cal BP**	**Age ka**	**North diff m**	**South diff m**	**Lake km^2 North**	**Lake km^2 Central**	**Lake km^2 South**	**Lake km^2 Total**
25	8260	7.45	4.10	-3.88	6220	790	500	
20	7560	6.65	3.28	-3.10	8280	1050	610	
15	6680	5.87	2.46	-2.33	11450	1210	860	
10	5510	4.75	1.64	-1.55	13070	1440	1280	
5	3750	3.5	0.82	-0.78	14250	1540	1600	
2.5	2350	2.35	0.41	-0.39				19090
0	0	0	-0	-0				23580

Column 1 - Present slopes of former lake levels used in a linear (planar) model to estimate former open-lake areas (Matile et al., this volume). Both linear and exponential models have these same slopes at Isobase 6.95, selected to equalize the vertical differences of their reconstructed lake surfaces at northern and southern ends of the lake.

Column 2 - Calendar age BP for the slope given in column 1, computed by the exponential model at Isobase 6.95.

Column 3 - Conventional ^{14}C age equivalent to calendar ages in column 2, using the calibration program Calib4.1.2 with its 1998 atmospheric decadal dat set (Stuiver and Reimer, 1993; Stuiver et al., 1998).

Column 4 - Computed vertical distance (m) that the exponential model lake surface is above the linear model lake surface at the northern end of the lake (Isobase 8.0) relative to Isobase 6.95 where the models are coincident.

Column 5 - Computed vertical distance (m) that the exponential model lake surface is below the linear model lake surface at the southern end of the lake (Isobase 5.6) relative to Isobase 6.95 where the models are coincident.

Column 6 - Water surface area at the elevation of the Warren Landing outlet sill (open lake) in the northern basin determined by the linear (planar) model (Matile et al., this volume).

Column 7 - Water surface area of impoundments behind outlet sills (open lake area) in the central basin determined by the linear (planar) model (Matile et al., this volume).

Column 8 - Water surface area at the elevation of the Hecla-Black outlet sill (open lake) in the southern basin determined by the linear (planar) model (Matile et al., this volume).

Column 9 - Water surface area at the elevation of the Jenpeg outlet (open lake area) for all of Lake Winnipeg determined by the linear (planar) model (Matile et al., this volume). The present lake area used in this report is 24,400 km^2 (National Hydrological Atlas, 1978).

Table 10. Component drainage basins of Lake Winnipeg's northern and southern basins

Component basin	Receiving basin	Period	Area km^2	Source and comment
Saskatchewan River	North Basin	4.7 to 0 ka	335 900	National Atlas of Canada (NAC), 1985
Manitoba-Winnipegosis	North Basin	7.7 to 0 ka	80 300	Last and Teller, 1983; includes estimated (this study) lake areas of 10 500 km^2
North Basin local[1]	North Basin	7.7 to 0 ka	82 730	This study; estimated from NAC, 1985, 1: 7 500 000 scale map
Central Basin local[2]	North Basin	7.7 to 0 ka	26 230	This study; estimated from NAC, 1985, 1: 7 500 000 scale map
Assiniboine River	North Basin South Basin	7.5 to ~/< 4 ka >7.5 & ~/< 4 ka	180 200	NAC, 1985; modified by moving lower 1800 km^2 to Red River basin
Red River	South Basin	~8 to 0 ka	107 300	NAC, 1985; see note above
Winnipeg River	South Basin	~8 to 0 ka	135 800	NAC, 1985
South Basin local[3]	Central/North Basin	~8 to 0 ka	10 670	This study; estimated from NAC, 1985, 1: 7 500 000 scale map
Sum			959 130	2.4 % less than the total Lake Winnipeg catchment given in NAC, 1985

[1] between Pigeon and Warren Landing sills; includes land and lake areas

[2] between Hecla-Black and Pigeon sills; includes land and lake areas

[3] south of Hecla-Black Sill; includes land and lake areas

Table 11. Hydrological parameters for analogue and other climates used in this study

Climate Name	Runoff q mm/yr	Potential Evap'n e_p mm/yr	Precipi-tation p mm/yr	Source or comment
Modern	145	700	550	Average of parameter ranges in Lake Winnipeg watershed from National Hydrological Atlas (NHA), 1978
Grassland Border	15	700	380	Selected from NHA, 1978 for the boundary zone between grassland and forest vegetation near Saskatoon, Saskatchewan
Central Grassland	4	940	300	Selected from NHA, 1978 for the drier area of grassland near Medicine Hat, Alberta
Central Grassland (suppressed runoff)	1	940	300	A drier version of the central grassland climate representing the effective climate in the desiccated mid-Holocene southern basin of Lake Winnipeg

Table 12. Scenarios of open/closed status for lakes in the Manitoba-Winnipegosis component basin

Climate scenario	Total Area A_b km2	Runoff q mm/yr	Potential Evap'n e_p mm/yr	Precipitation p mm/yr	Climate Supportable Area A km^2	Closed or open status i.e. no overflow or overflow to North Basin[1]
1. When Assiniboine River flows to Red River and South basin, bypassing Lake Manitoba						
Central Grassland	80300	4	940	300	499	Closed
Grassland Border	80300	15	700	380	3596	Closed
Modern Lake Winnipeg average	80300	145	700	550	39469	Open
2. When Assiniboine River flows to Lake Manitoba						
Central Grassland	260500	4	940	300	1618	Closed
Grassland Border	260500	15	700	380	9892	Probably closed, possibly seasonally open
Modern Lake Winnipeg average	260500	145	700	550	128042	Open

[1] Closed if supportable area is <10 500 km^2, the present combined area of lakes Manitoba and Winnipegosis and Dauphin Lake (areas from G.L.D. Matile, personal communication, 1999)

Table 13. Scenarios of open/closed status for lakes in the central sub-basin of Lake Winnipeg

Climate scenario	Total Area A_b km2	Runoff q mm/yr	Potential Evap'n e_p mm/yr	Precipitation p mm/yr	Climate Supportable Area A km^2	Closed or open status[1]
Central Grassland	26230	4	940	300	163	Closed
Grassland Border	26230	15	700	380	1174	Open initially, closed by 5.9 ka
Modern Lake Winnipeg average	26230	145	700	550	12890	Open

[1] Closed if A < computed open lake area for Central Lake area in Table 9

Table 14. Lake Winnipeg South Basin, catchment areas and climate-supportable lake areas

Age Cal BP/ ka	Component drainage basins					Analogue Climate	Runoff q mm/yr	Potential Evap'n e_p mm/yr	Precipi-tation p mm/yr	Climate Supportable Area A km²
	Assiniboine R. km²	Red River km²	Winnipeg River km²	South Basin & local km²	Total Area A_b km²					
8260/ 7.5	180200	107300	135800	10670	433970	Grassland Border	15	700	380	19431
	180200	107300	135800	10670	433970	Central Grassland	4	940	300	2695
	180200	107300	135800	10670	433970	Central Grassland sr[1]	1	940	300	677
8260/ 7.5	0	107300	135800	10670	253770	Grassland Border	15	700	380	11363
	0	107300	135800	10670	253770	Central Grassland	4	940	300	1576
	0	107300	135800	10670	253770	Central Grassland sr	1	940	300	396
7560/ 6.7	0	107300	135800	10670	253770	Grassland Border	15	700	380	11363
	0	107300	135800	10670	253770	Central Grassland	4	940	300	1576
	0	107300	135800	10670	253770	Central Grassland sr	1	940	300	396
6680/ 5.9	0	107300	135800	10670	253770	Grassland Border	15	700	380	11363
	0	107300	135800	10670	253770	Central Grassland	4	940	300	1576
	0	107300	135800	10670	253770	Central Grassland sr	1	940	300	396
5510/ 4.8	0	107300	135800	10670	253770	Grassland Border	15	700	380	11363
	0	107300	135800	10670	253770	Central Grassland	4	940	300	1576
	0	107300	135800	10670	253770	Central Grassland sr	1	940	300	396
4440/ 4.0	0	107300	135800	10670	253770	Grassland Border	15	700	380	11363
	0	107300	135800	10670	253770	Central Grassland	4	940	300	1576
	0	107300	135800	10670	253770	Central Grassland sr	1	940	300	396
4440/ 4.0	180200	107300	135800	10670	433970	Grassland Border	15	700	380	19431
	180200	107300	135800	10670	433970	Central Grassland	4	940	300	2695
	180200	107300	135800	10670	433970	Central Grassland sr	1	940	300	677

3750/ 3.5	180200	107300	135800	10670	433970	Grassland Border	15	700	380	19431
	180200	107300	135800	10670	433970	Central Grassland	4	940	300	2695
	180200	107300	135800	10670	433970	Central Grassland sr	1	940	300	677
3060/ 2.9	180200	107300	135800	10670	433970	Grassland Border	15	700	380	19431
	180200	107300	135800	10670	433970	Central Grassland	4	940	300	2695
	180200	107300	135800	10670	433970	Central Grassland sr	1	940	300	677

[1] Central Grassland sr = Central Grassland climate with suppressed runoff

Table 15a. Lake Winnipeg North Basin, catchment areas for modelled ages and selected basin climates

Age Cal BP/ ka	Component drainage basins								Total Area A_b km^2	Notes and sub-basin lake status
	Saskatchewan River (SR) km^2	Manitoba-Winnipegosis(MW) km^2	Assiniboine River (AR) km^2	North Basin (NB) & local area km^2	Central Basin (CB) & local area km^2	South Basin (SB) & local area km^2	Red River (RR) km^2	Winnipeg River(WR) km^2		
8260/ 7.5	0	0	180200	82730	26230	10670	107300	135800	542930	AR to SB; SB open and MW closed
	0	0	180200	82730	26230	10670	107300	135800	542930	AR to SB; SB open and MW closed
8260/ 7.5	0	80300	180200	82730	0	0	0	0	343230	AR to MW; MW open; SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
7560/ 6.7	0	80300	180200	82730	0	0	0	0	343230	MW open; SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
6680/ 5.9	0	80300	180200	82730	0	0	0	0	343230	MW open; SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
5510/ 4.8	0	80300	180200	82730	0	0	0	0	343230	MW open; SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
5330/ 4.7	0	80300	180200	82730	0	0	0	0	343230	MW open; SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
	0	0	0	82730	0	0	0	0	82730	MW & SB+CB closed
5330/ 4.7	335900	80300	180200	82730	0	0	0	0	679130	SR to NB. MW open; SB+CB closed
	335900	0	0	82730	0	0	0	0	418630	MW & SB+CB closed
	335900	0	0	82730	0	0	0	0	418630	MW & SB+CB closed

4440/ 4.0	335900	80300	180200	82730	0	0	0	0	679130	MW open; SB-CB closed
	335900	0	0	82730	0	0	0	0	418630	MW & SB+CB closed
	335900	0	0	82730	0	0	0	0	418630	MW & SB+CB closed
4440/ 4.0	335900	80300	180200	82730	26230	10670	107300	135800	959130	MW(10500) & SB(1475)&CB(1300) open
	335900	0	180200	82730	26230	10670	107300	135800	878830	MW closed; SB(1475)+CB(1300) open
3750/ 3.5	335900	80300	180200	82730	26230	10670	107300	135800	959130	MW(10500) & SB(1600)+CB(1540) open
	335900	0	180200	82730	26230	10670	107300	135800	878830	MW closed; SB(1600)+CB(1540) open
3060/ 2.9	335900	80300	180200	82730	26230	10670	107300	135800	959130	MW & SB(2729)+CB(1570) open
	335900	0	180200	82730	26230	10670	107300	135800	878830	MW closed; SB(2729)+CB(1570) open
3060/ 2.9	335900	80300	180200	82730	26230	10670	107300	135800	959130	NB,CB,SB coalesce; MW & SB-CB open
	335900	0	180200	82730	26230	10670	107300	135800	878830	MW closed; SB-CB open
2350/ 2.4	335900	80300	180200	82730	26230	10670	107300	135800	959130	MW & SB-CB open
	335900	0	180200	82730	26230	10670	107300	135800	878830	MW closed; SB-CB open
0/ 0	335900	80300	180200	82730	26230	10670	107300	135800	959130	MW & SB-CB open
	335900	0	180200	82730	26230	10670	107300	135800	878830	MW closed; SB-CB open
	335900	80300	180200	82730	26230	10670	107300	135800	959130	MW & SB-CB open

Table 15b. Lake Winnipeg North Basin, climate supportable lake areas for modelled ages and selected climates

Age Cal BP/ ka	TotalArea A_t km^2 (from Table 15a)	Analogue Climate[3] Assignment	Runoff q mm/yr	Potential Evapor-ation e_p mm/yr	Precipit-ation p mm/yr	Climate Support-able lake A km^2	less up-stream lake area km^2 (see Notes Table 15a)	North Basin ClimateSupp-ortable area km^2
8260/ 7.5	542930	GB in all basins	15	700	380	24310	500	23810
	542930	CG in all basins	4	940	300	3372	500	2872
8260/ 7.5	343230	GB in NB, MW. CGrs in SB&CB	15	700	380	15369	10500	4869
	82730	GB in NB, MW. CGrs in SB&CB	15	700	380	3704	0	3704
	82730	CG in all basins	4	940	300	514	0	514
7560/ 6.7	343230	GB in NB, MW. CGrs in SB&CB	15	700	380	15369	10500	4869
	82730	GB in NB, MW. CGrs in SB&CB	15	700	380	3704	0	3704
	82730	CG in all basins	4	940	300	514	0	514
6680/ 5.9	343230	GB in NB, MW. CGrs in SB&CB	15	700	380	15369	10500	4869
	82730	GB in NB, MW. CGrs in SB&CB	15	700	380	3704	0	3704
	82730	CG in all basins	4	940	300	514	0	514
5510/ 4.8	343230	GB in NB, MW. CGrs in SB&CB	15	700	380	15369	10500	4869
	82730	GB in NB, MW. CGrs in SB&CB	15	700	380	3704	0	3704
	82730	CG in all basins	4	940	300	514	0	514
5330/ 4.7	343230	GB in NB, MW. CGrs in SB&CB	15	700	380	15369	10500	4869
	82730	GB in NB, MW. CGrs in SB&CB	15	700	380	3704	0	3704
	82730	CG in all basins	4	940	300	514	0	514
5330/ 4.7	679130	GB in NB, MW. CGrs in SB&CB	15	700	380	30409	10500	19909
	418630	GB in NB, MW. CGrs in SB&CB	15	700	380	18745	0	18745
	418630	CG in all basins	4	940	300	2600	0	2600

4440/ 4.0	679130	GB in NB, MW. CGrs in SB&CB	15	700	380	30409	10500	19909
	418630	GB in NB, MW. CGrs in SB&CB	15	700	380	18745	0	18745
	418630	CG in all basins	4	940	300	2600	0	2600
4440/ 4.0	959130	GB in all basins	15	700	380	42946	13275	29671
	878830	CG in NB, MW. CG in SB&CB	4	940	300	5459	2775	2684
3750/ 3.5	959130	GB in all basins	15	700	380	42946	13640	27706
	878830	CG in NB, MW. CG in SB&CB	4	940	300	5459	3140	2319
3060/ 2.9	959130	GB in all basins	15	700	380	42946	14799	28147
	878830	CG in NB, MW. CG in SB&CB	4	940	300	5459	4299	1160
3060/ 2.9	959130	GB in all basins	15	700	380	42946	10500	32446
	878830	CG in NB, MW. CG in SB&CB	4	940	300	5459	0	5459
2350/ 2.4	959130	GB in all basins	15	700	380	42946	10500	32446
	878830	CG in NB, MW. CG in SB&CB	4	940	300	5459	0	5459
0/ 0	959130	GB in all basins	15	700	380	42946	10500	32446
	878830	CG in NB, MW. CG in SB&CB	4	940	300	5459	0	5459
	959130	Modern (average of parameter ranges)	145	700	550	471437	10500	460937

[3] GB = Grassland Border climate; CG = Central Grassland climate; CGrs = Central Grassland (suppressed runoff)

[4] SB = South Basin; CB = Central Basin; MW = Manitoba-Winnipegosis basin

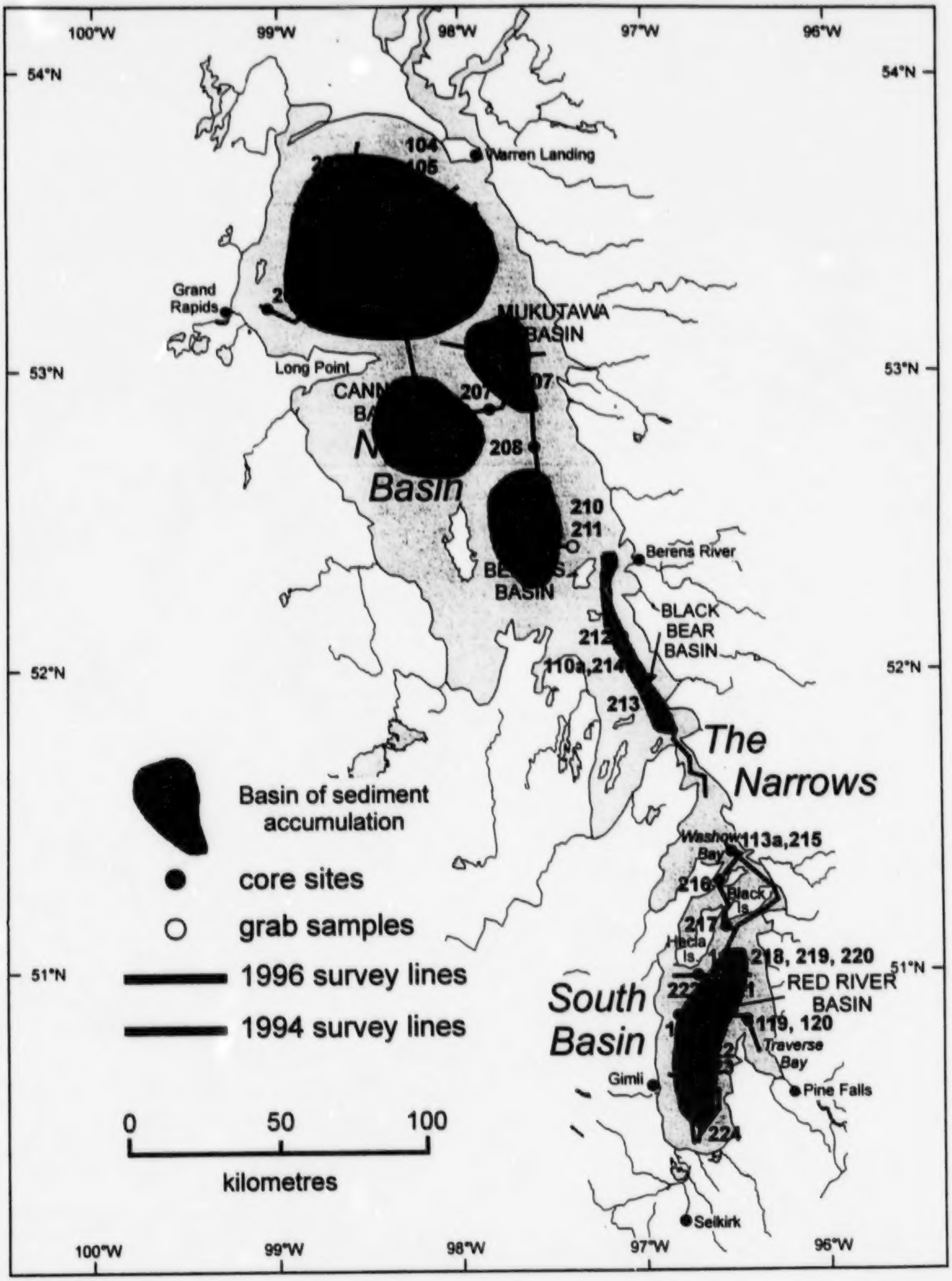

100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
104
105
Warren Landing
Grand Rapids
MUKUTAWA BASIN
Long Point
CANN
BA
207
07
208
N
Basin
210
211
Berens River
BE S
BASIN
BLACK BEAR BASIN
212
110a,214
213
The Narrows
Basin of sediment accumulation
core sites
grab samples
1996 survey lines
1994 survey lines
0
50
100
kilometres
Washow Bay
113a,215
216
Black Is.
217
Hecla Is.
218, 219, 220
RED RIVER BASIN
South Basin
119, 120
Traverse Bay
Gimli
Pine Falls
224
Selkirk

Figure 1. Map of Lake Winnipeg showing 1996 and 1994 core sites on 1996 and 1994 survey lines. Depocentres after Brunskill and Graham (1979).

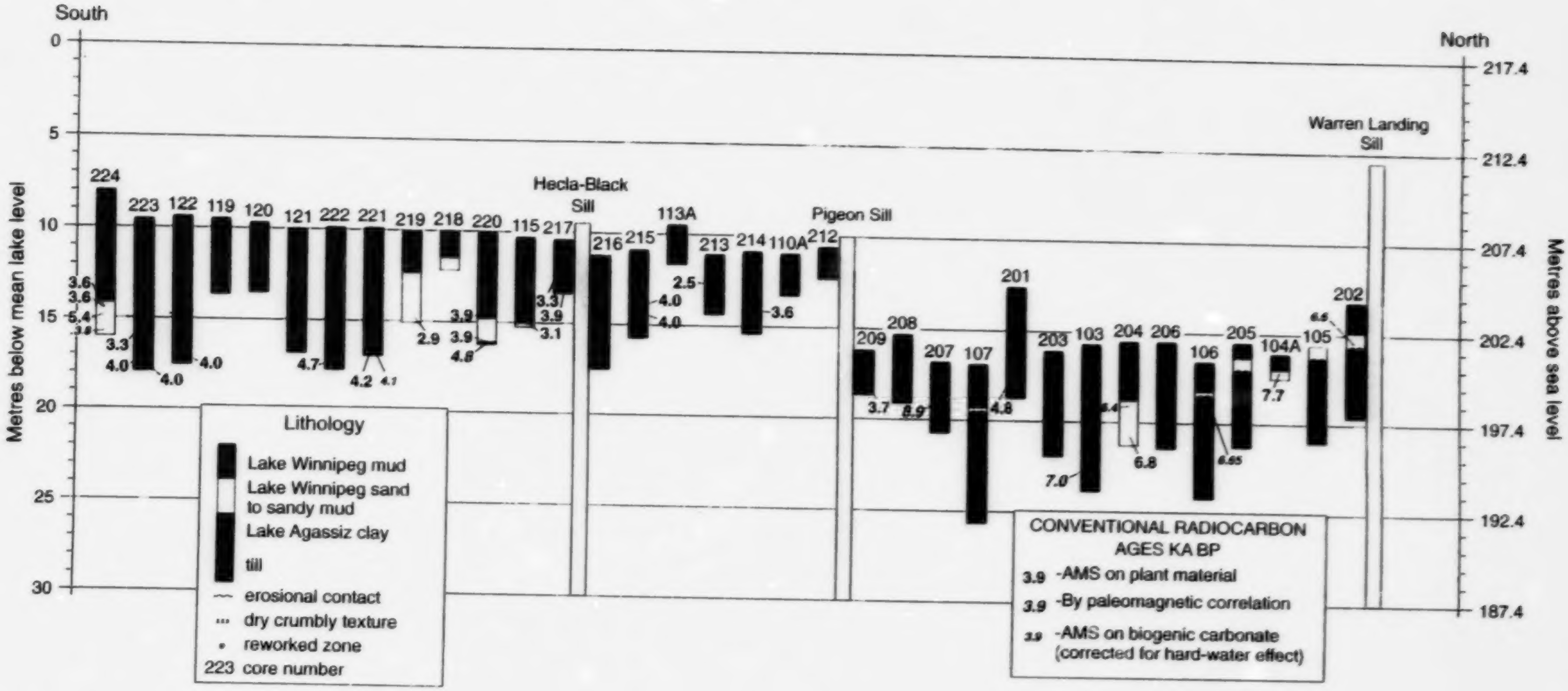


Figure 2. South-north distribution of core, equally spaced for clarity, showing abbreviated core sediment units with radiocarbon ages plotted versus elevation/depth. The depth/elevations of the core tops and contacts with Lake Agassiz sediment or base of Lake Winnipeg mud are determined by acoustic and seismic reflection sounding (Table 3). Note that no horizontal scale is indicated as this diagram is scaled in the vertical direction only.

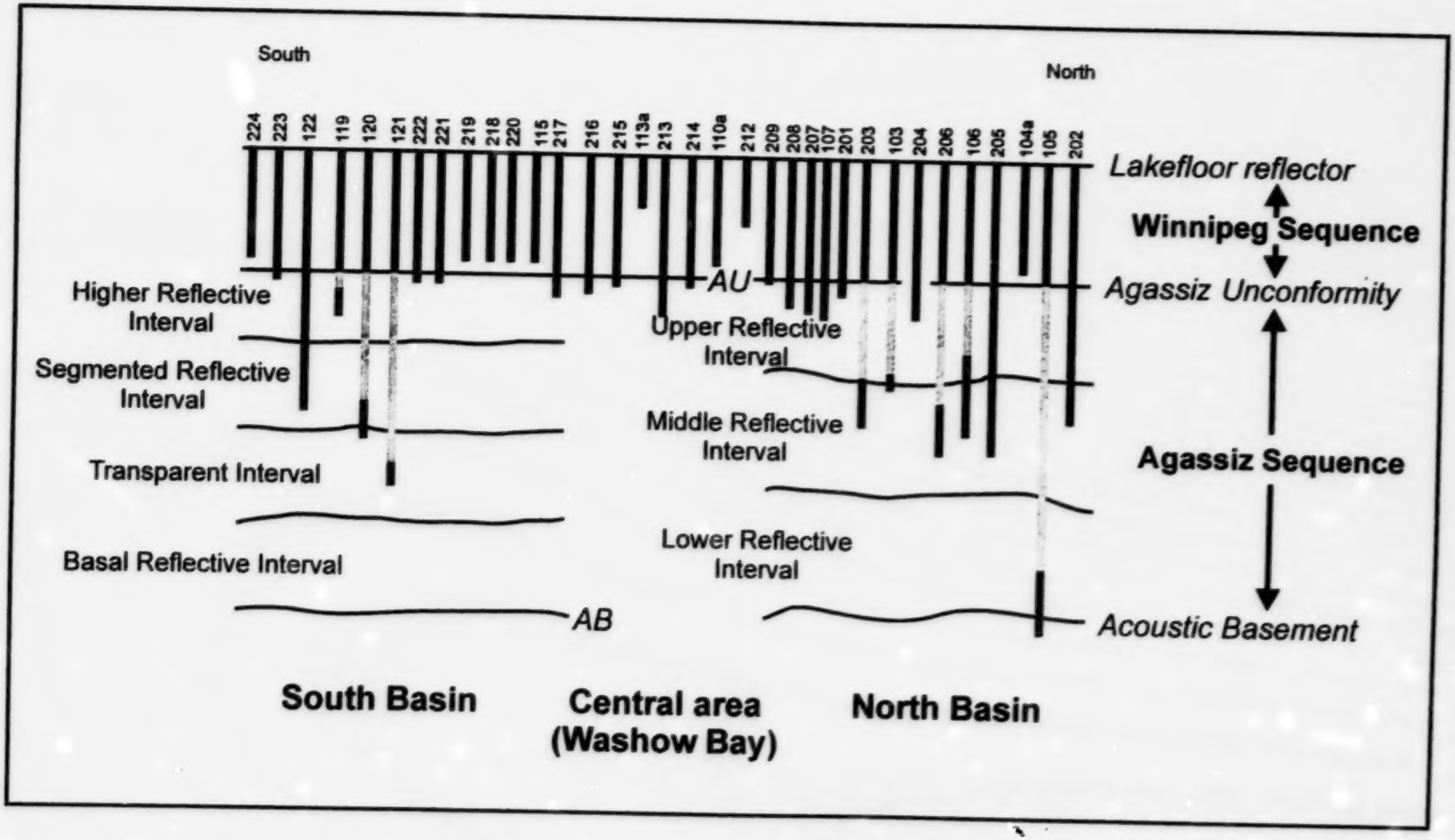

South
North
224
223
122
119
120
121
222
221
219
218
220
115
217
216
215
113a
213
214
110a
212
209
208
207
107
201
203
103
204
206
106
205
104a
105
202
Lakefloor reflector
Winnipeg Sequence
Agassiz Unconformity
AU
Agassiz Sequence
Acoustic Basement
AB
Higher Reflective Interval
Segmented Reflective Interval
Transparent Interval
Basal Reflective Interval
Upper Reflective Interval
Middle Reflective Interval
Lower Reflective Interval
South Basin
Central area (Washow Bay)
North Basin

Figure 3. Schematic of 1996 and 1994 core penetration of seismic sequences and intervals (vertical lines, solid portions). The light vertical intervals indicate missing (eroded) section at the Agassiz Unconformity (AU). AB represents Acoustic Basement.

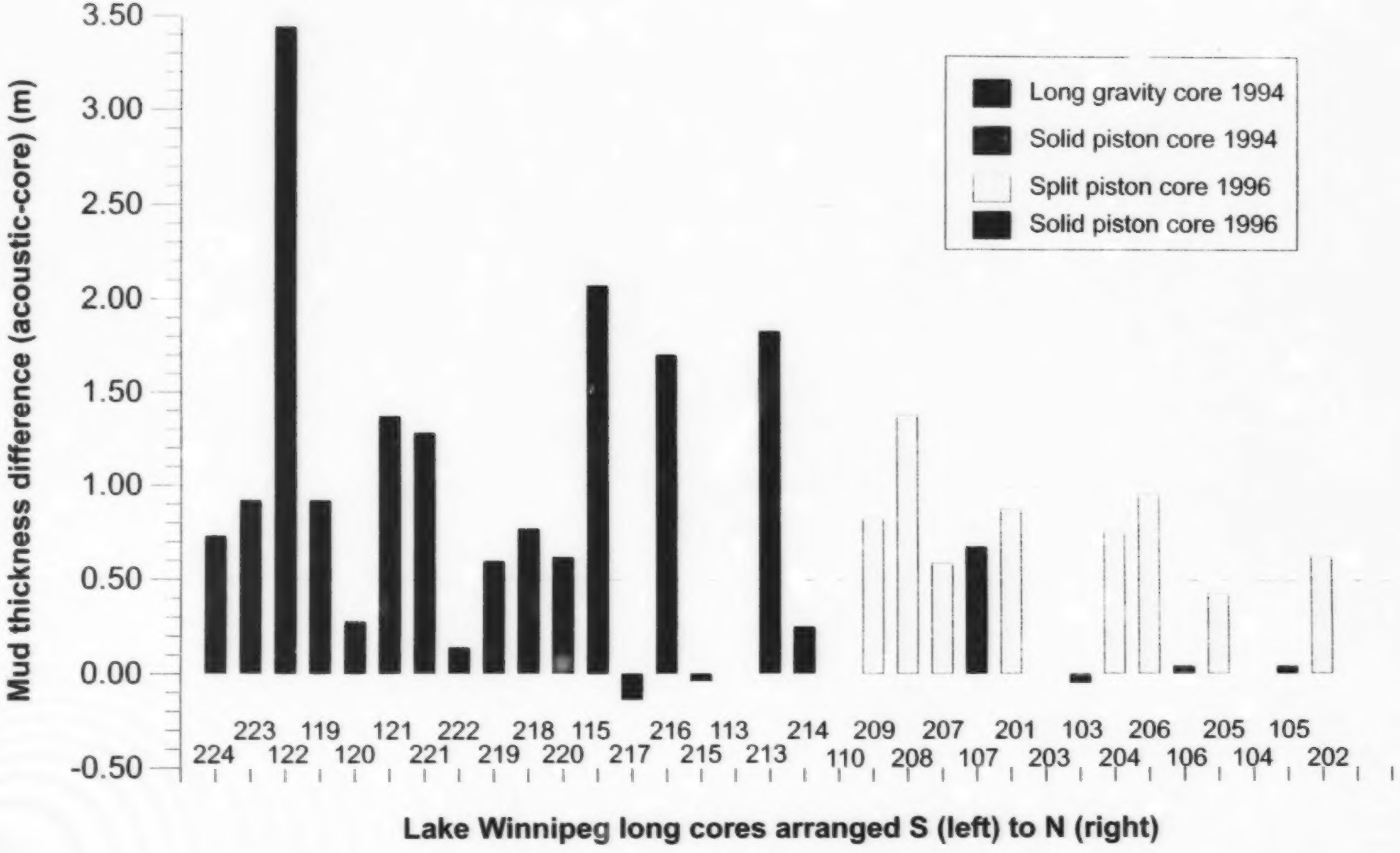


Figure 4. Differences in mud thickness by seismic sounding and cored mud length at core sites plotted north-south.

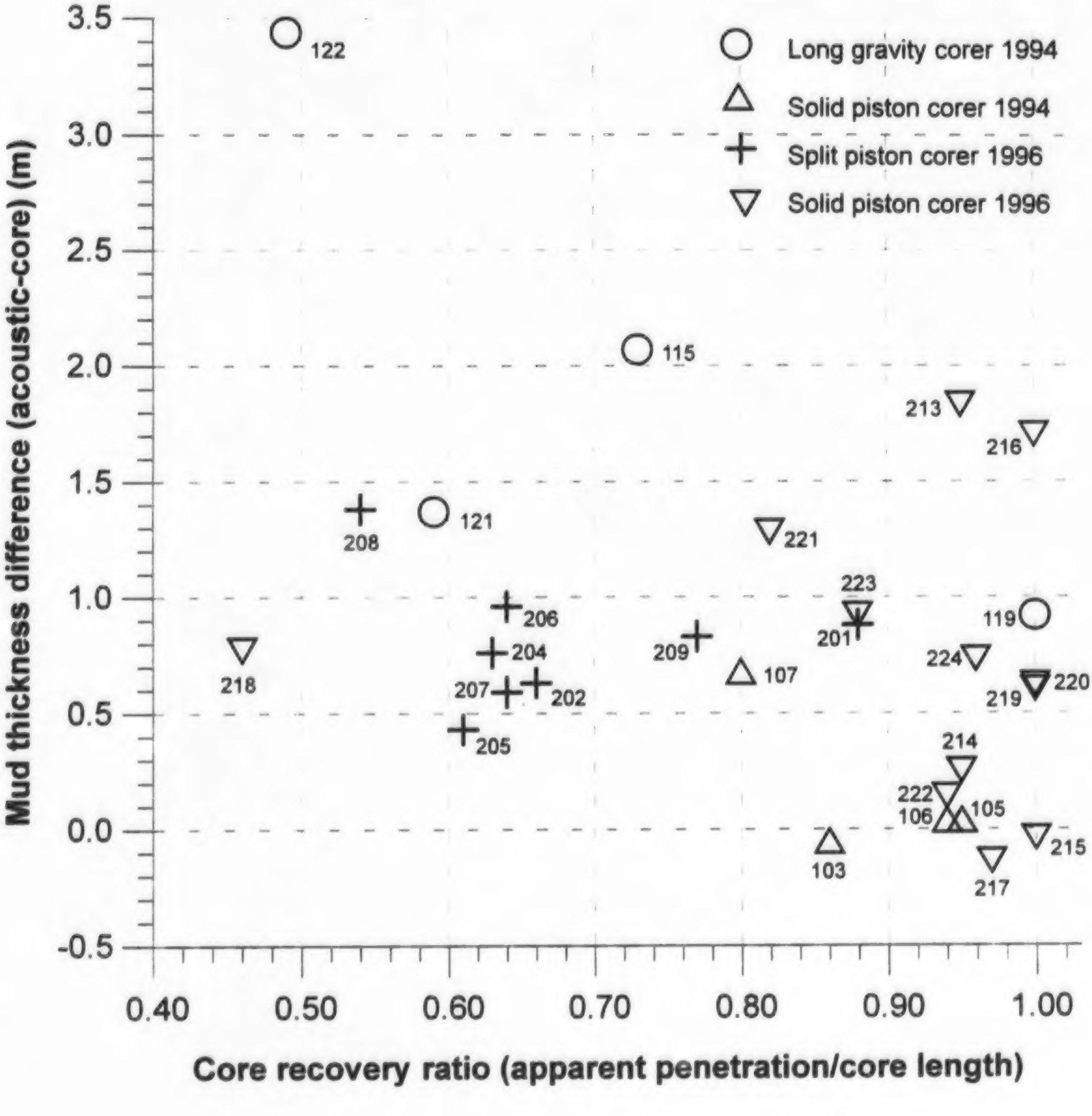
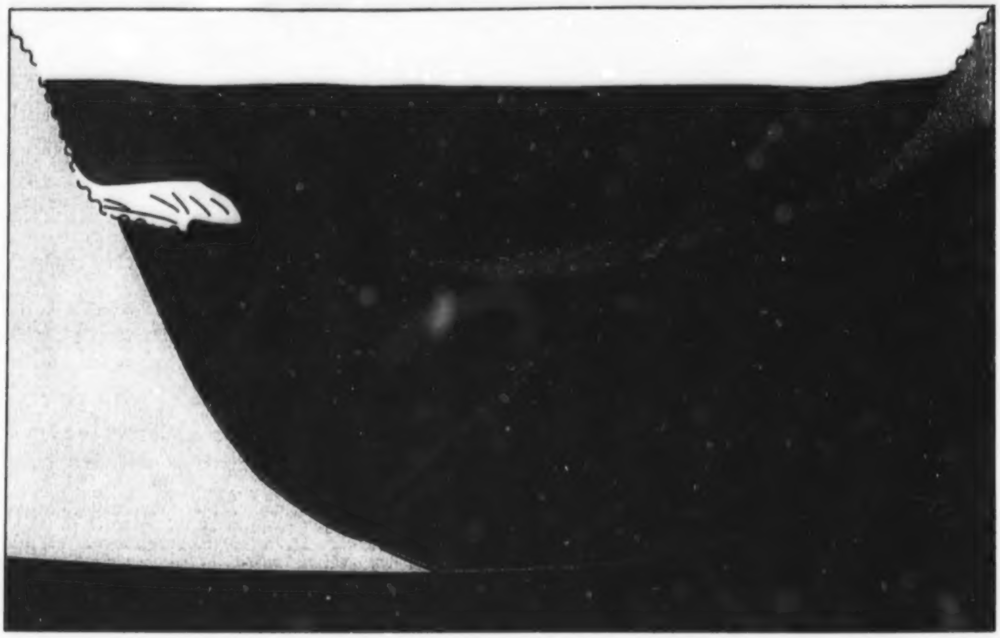


Figure 5. Plot of mud thickness deficit (acoustic measurement minus core length) versus core recovery ratio.

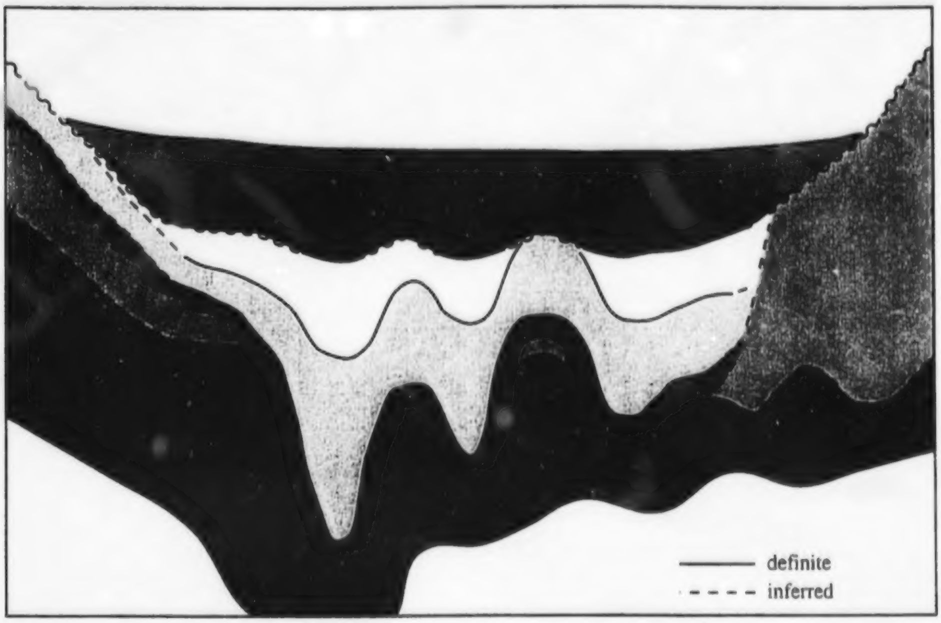
South Basin, Lake Winnipeg



Sequence	Seismic Stratigraphy	Seismic Facies	Lithology
Winnipeg Sequence - WS			
▨	WS Upper Facies	transparent	soft, silt-clay mud
■	WS Lower Facies	weak, discontinuous, coherent reflections	soft mud with banding silt laminations
	WS Subfaciees	clinoforms	well-sorted sand
〰 〰 〰 〰	Agassiz Unconformity - AU	strong reflection truncating underlying reflections	WS basal muddy silt or sand over desiccated AS surface 〰〰〰 ■
Agassiz Sequence - AS			
▨	Higher Reflective Interval - HRI	strong, parallel, coherent reflections	banded silty clay
■	Segmented Reflective Interval - SRI	widely spaced, coherent reflections	alternating massive silty clay and rhythmites
■	Transparent Reflective Interval - TRI	disseminated, incoherent reflections	massive silty clay
■	Basal Reflective Interval - BRI	strong parallel, coherent reflections	laminated silt and silty clay
Acoustic Basement - AB			
░	Till	Chaotic reflection pattern	poorly-sorted sediment
■	Bedrock	reflection free	Paleozoic sedimentary rocks, Precambrian metamorphic rocks

Figure 6. Generalized seismo- and litho-stratigraphy of South Basin.

Northern North Basin, Lake Winnipeg



Sequence	Seismic Stratigraphy	Seismic Facies	Lithology
Winnipeg Sequence - WS			
▒	WS Upper Facies	transparent	soft, silt-clay mud
■	WS Lower Facies	weak, discontinuous, coherent reflections	soft mud with banding silt laminations
∼∼ ∼∼ ∼∼ ∼∼	Agassiz Unconformity - AU	strong reflection truncating underlying reflections	WS basal muddy silt or sand ■
Agassiz Sequence - AS			
□	Upper Reflective Interval - URI	strong, parallel, coherent reflections over a transparent zone	rhythmically bedded to laminated silty clay with silt laminations
░	Middle Reflective Interval - MRI	strong, parallel, coherent reflections over a transparent zone	
■	Lower Reflective Interval - LRI	strong, parallel, coherent reflections	
Acoustic Basement - AB			
▒	Till	Chaotic reflection pattern	poorly-sorted sediment
■	Bedrock	reflection free	Paleozoic sedimentary rocks, Precambrian metamorphic rocks

Figure 7. Generalized seismo- and litho-stratigraphy of North Basin.

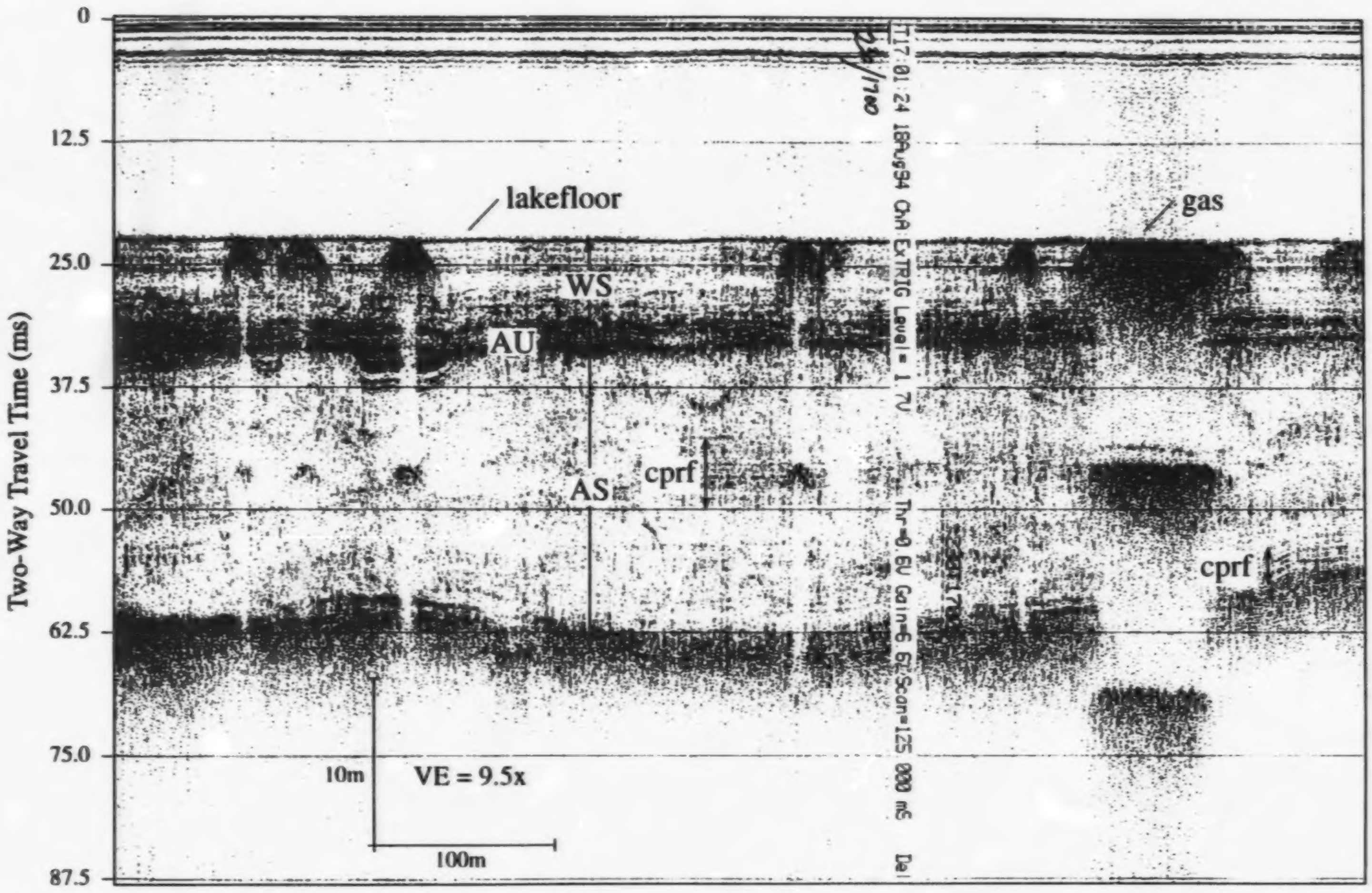


Figure 8a. Seistec profile showing disturbed facies with segments of undeformed coherent reflections in the Agassiz Sequence southeast of Long Point, North Basin.

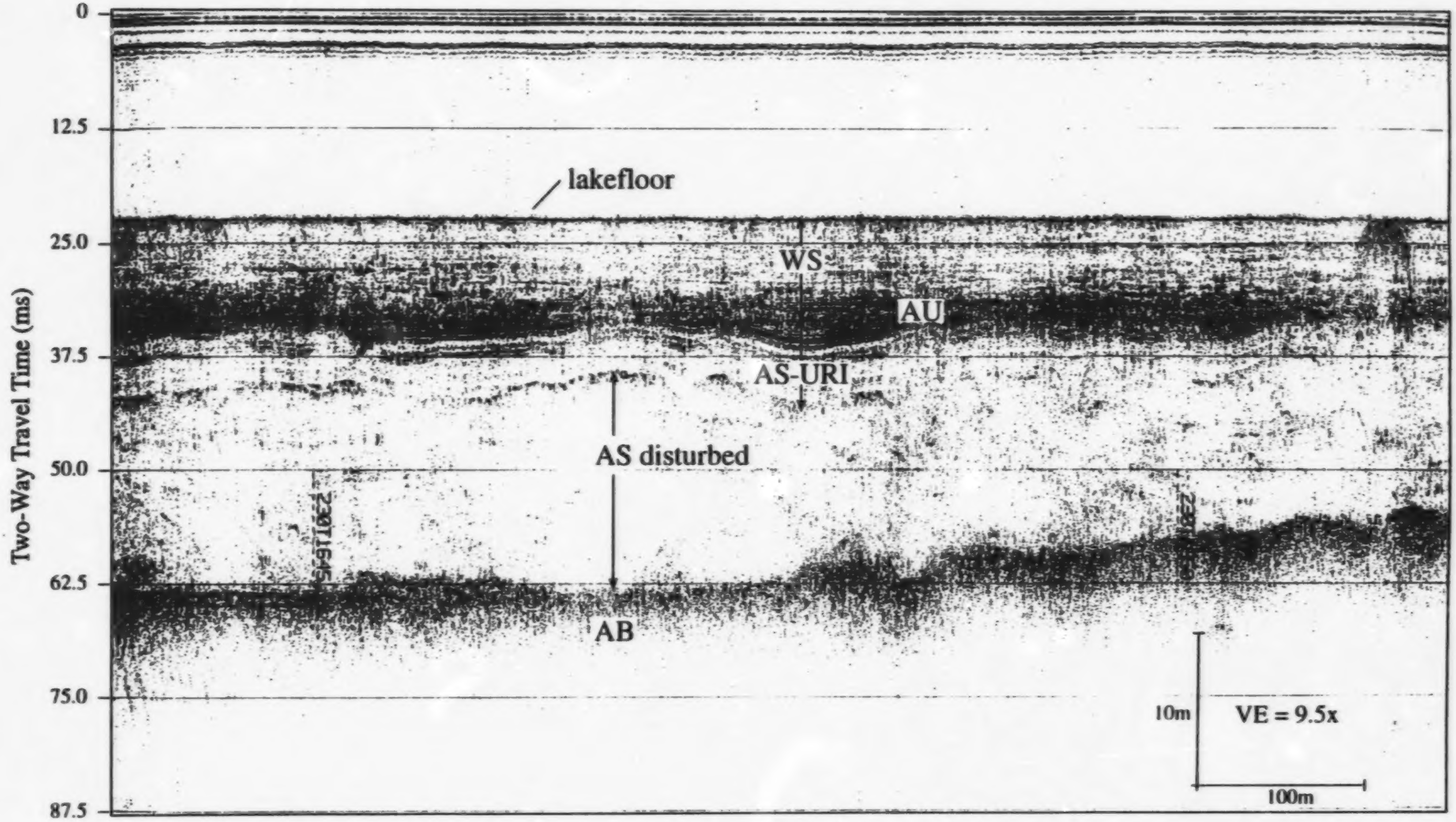


Figure 8b. Seistec profile showing the undisturbed Upper Reflective Interval (URI) overlying the disturbed facies of the Agassiz Sequence southeast of Long Point, North Basin.

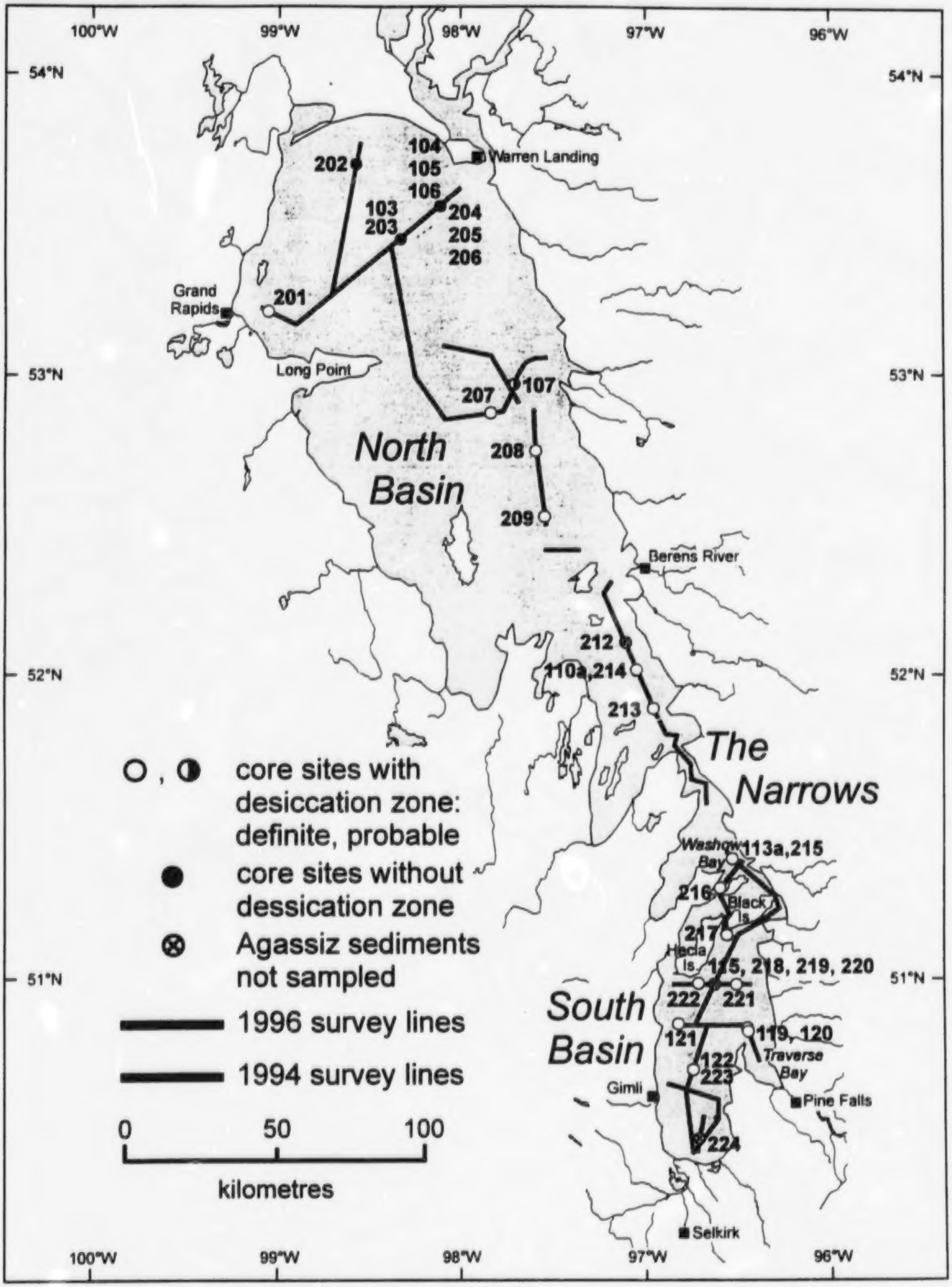

100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
Warren Landing
Grand Rapids
Long Point
Berens River
North Basin
The Narrows
South Basin
Washow Bay
Black Is.
Hecla Is.
Traverse Bay
Gimli
Pine Falls
Selkirk
202
104
105
106
103
203
204
205
206
201
207
107
208
209
212
110a,214
213
113a,215
216
217
115, 218, 219, 220
222
221
121
119, 120
122
223
224
○ , ◑ core sites with desiccation zone: definite, probable
● core sites without dessication zone
⊗ Agassiz sediments not sampled
1996 survey lines
1994 survey lines
0
50
100
kilometres

Figure 9. Map showing locations of core sites with and without a desiccation zone (crumbly dry texture or enhanced strength) in the uppermost Agassiz sediment.

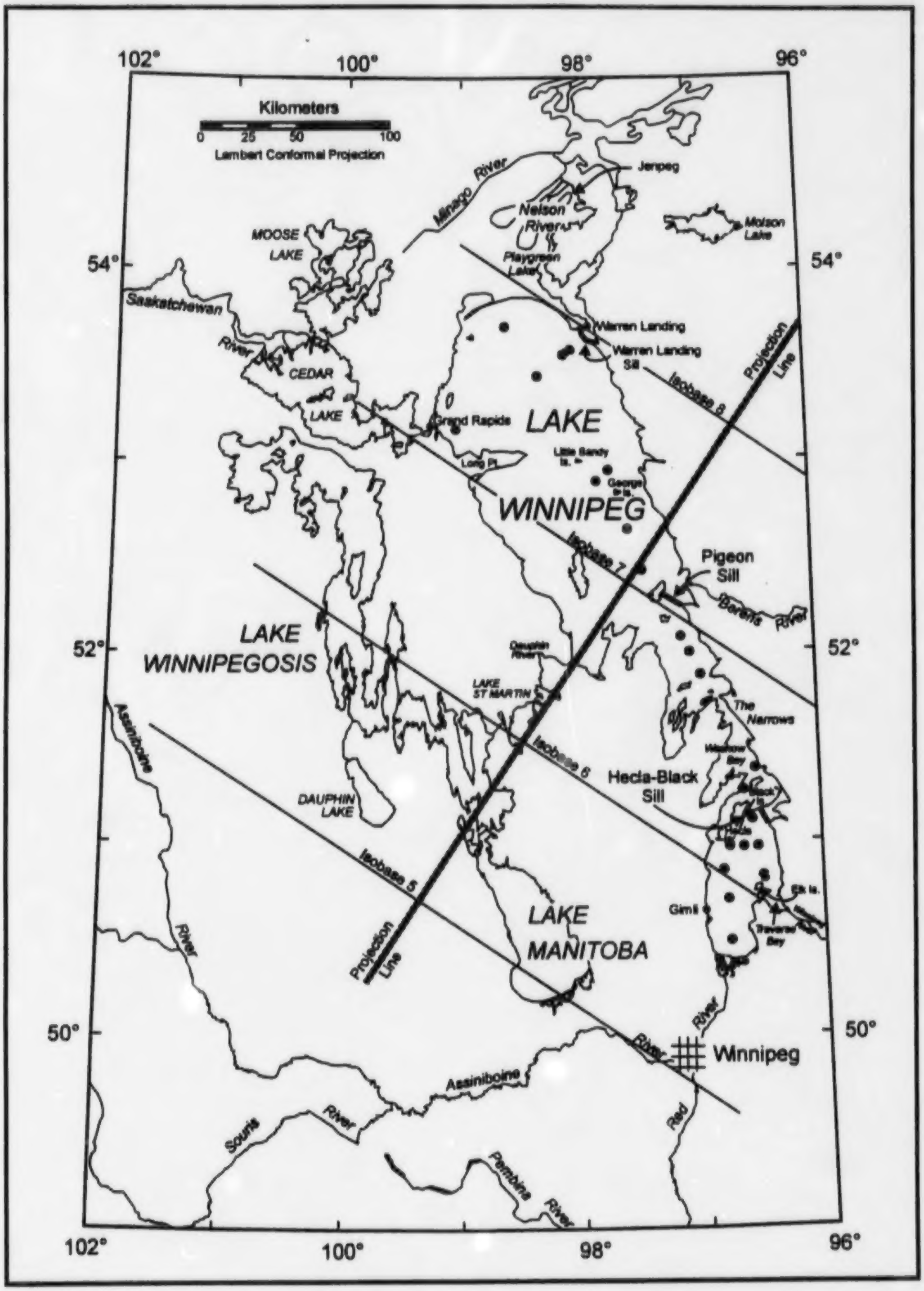

102°
100°
98°
96°
Kilometers
0 25 50 100
Lambert Conformal Projection
Minago River
Jenpeg
Nelson River
Playgreen Lake
Molson Lake
MOOSE LAKE
54°
Saskatchewan River
CEDAR LAKE
Warren Landing
Warren Landing Sill
Isobase 8
Projection Line
Grand Rapids
LAKE WINNIPEG
Long Pt.
Little Sandy Is.
George Is.
Isobase 7
Pigeon Sill
Berens River
LAKE WINNIPEGOSIS
52°
Dauphin River
LAKE ST MARTIN
The Narrows
Isobase 6
Hecla-Black Sill
Assiniboine
DAUPHIN LAKE
Isobase 5
Gimli
Elk Is.
Traverse Bay
LAKE MANITOBA
Projection Line
River
50°
Red River
Winnipeg
Assiniboine
Souris River
Pembina River

Figure 10. Regional map of southern Manitoba showing isobases of equal post-Agassiz differential uplift (Teller and Thorleifson, 1983), Lake Winnipeg, Dauphin Lake, Lake Winnipegosis, Cedar Lake, Moose Lake, and core locations (black dots).

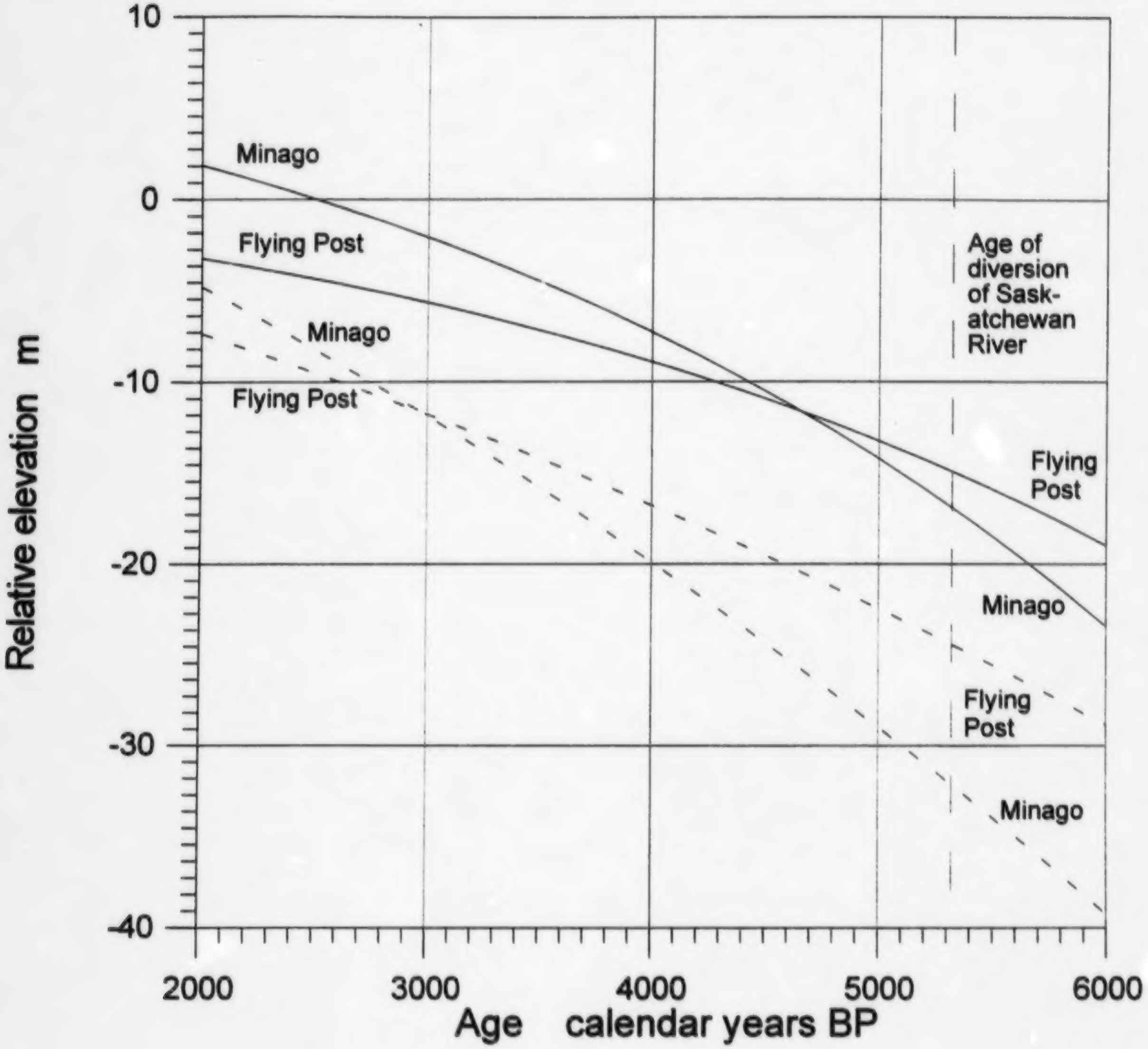


Figure 11. Comparison of the performance of two exponential uplift models with respect to the independently-determined age (vertical dashed line at 5320 cal BP, 4.65 ka) of the diversion of the Saskatchewan River from Minago River (Isobase 7.8) (Fig. 10) over a till barrier at Flying Post Rapids (Isobase 6.95) into Lake Winnipeg at Grand Rapids (Fig. 10). The uplift models are of the decaying exponential type. Their relaxation times, tau, were separately evaluated based on shoreline tilt data (Tackman et al., 1998) from Dauphin Lake (Fig. 10)(D)(tau=8000 years), and from Lake Winnipegosis (Fig. 10)(W)(tau=3500 years). River diversion occurred when the Minago elevation approached that of the Flying Post till barrier. Clearly, the diversion is better represented by the model based on data from the Lake Winnipegosis area. See text for further discussion.

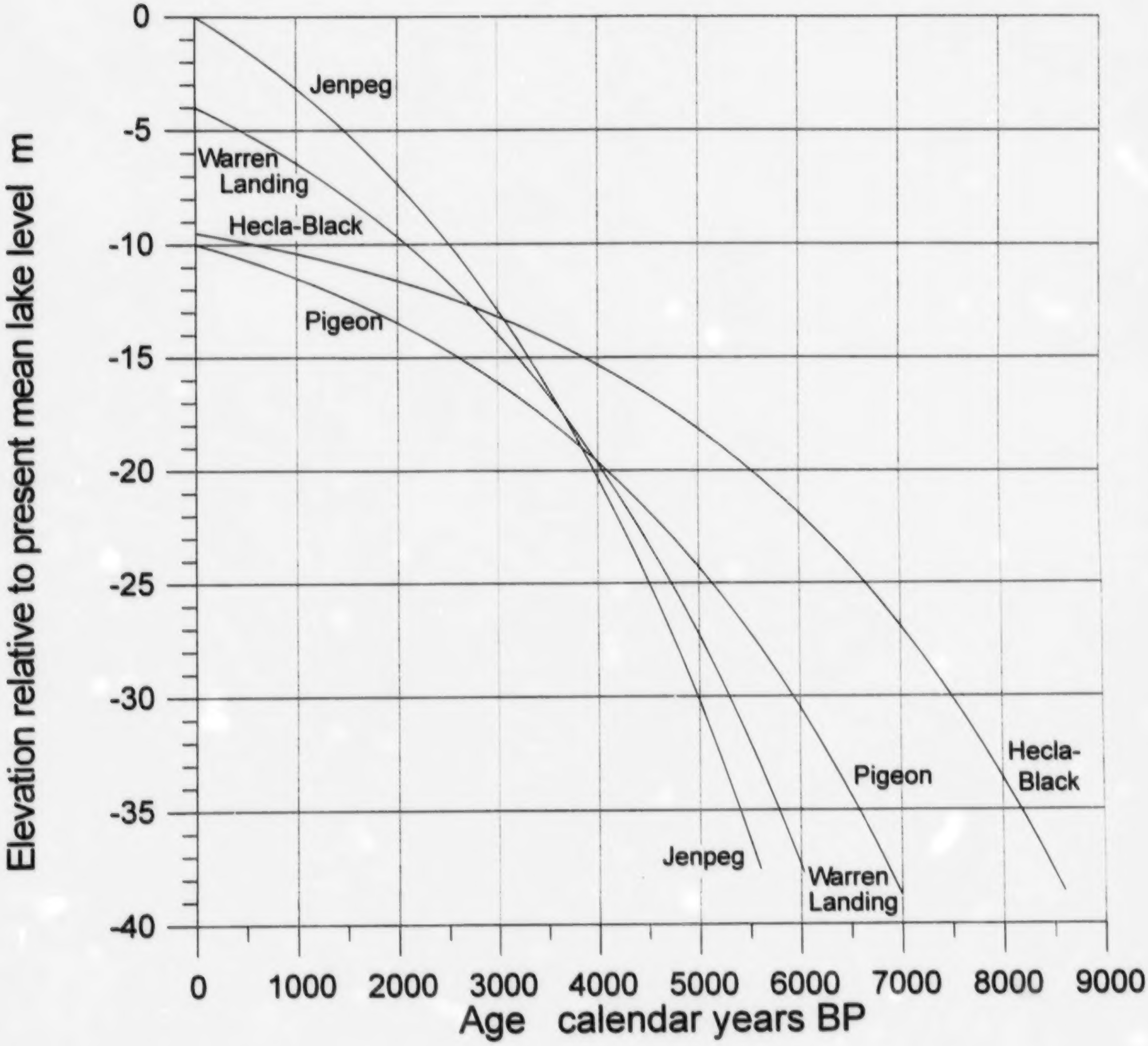


Figure 12. Modelled uplift histories of outlet sills (thresholds) (Fig. 10) which controlled overflow water levels in major sub-basins of Lake Winnipeg. Elevations in metres are relative to 214.7 m, the present mean elevation above sea level of Lake Winnipeg. Lake waters in sub-basins coalesced as more-rapidly-rebounding northern sills overtook southern sills. See text for further discussion.

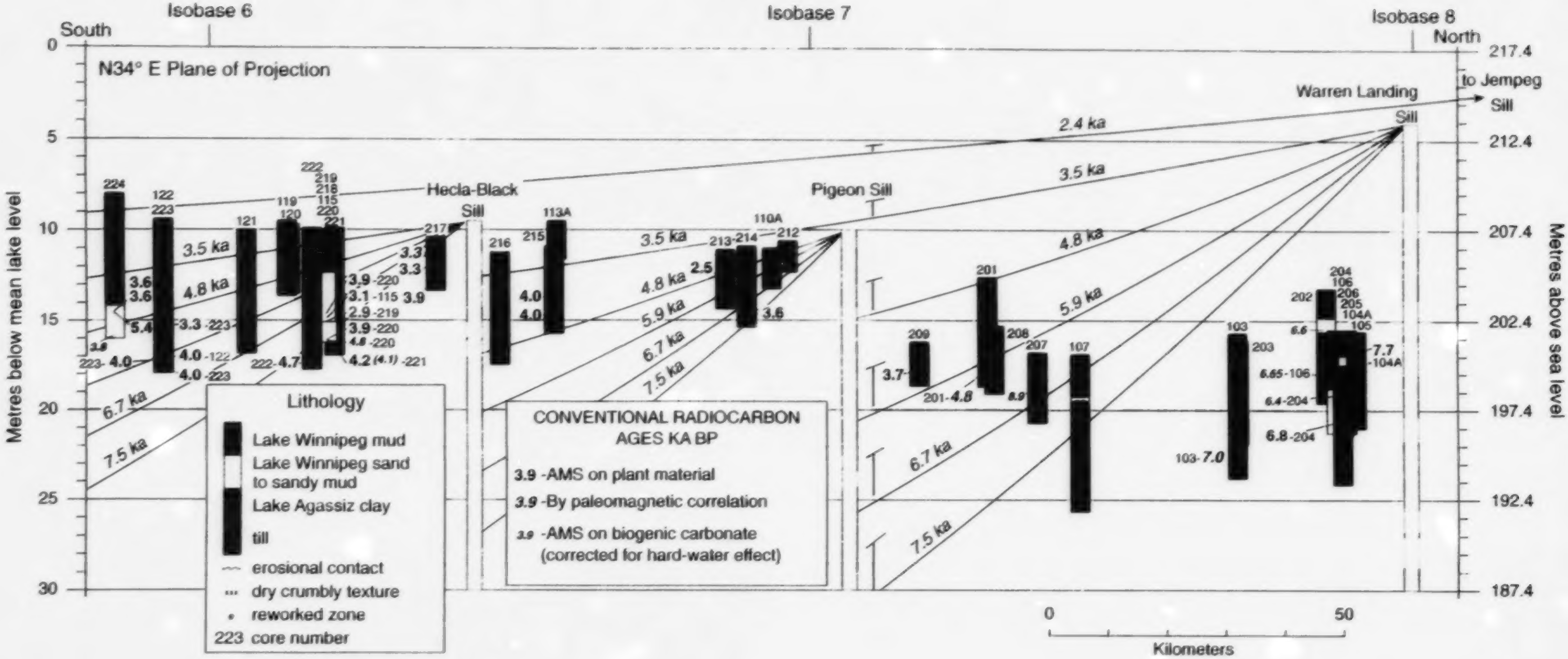


Figure 13. Core logs, showing abbreviated litho-stratigraphy and basal conventional radiocarbon dates at the base of the Lake Winnipeg sediments as in Figure 2, projected onto the plane (N34° E)(Teller and Thorleifson, 1983) of maximum uplift-driven tilt. Also shown are the principal sills which controlled water level of open, overflowing lakes in the sub-basins of Lake Winnipeg. Paleolake surfaces as computed by the exponential uplift model are shown for 6 phases prior to present. The vertical lines and bars rising from each modelled lake surface (north of Pigeon Sill) indicate the deviation in elevation between the exponential uplift model and the linear tilt model over a horizontal run of 90 km. The linear model was used to estimate areas of the former 6 lake phases in Matile et al., (this volume).

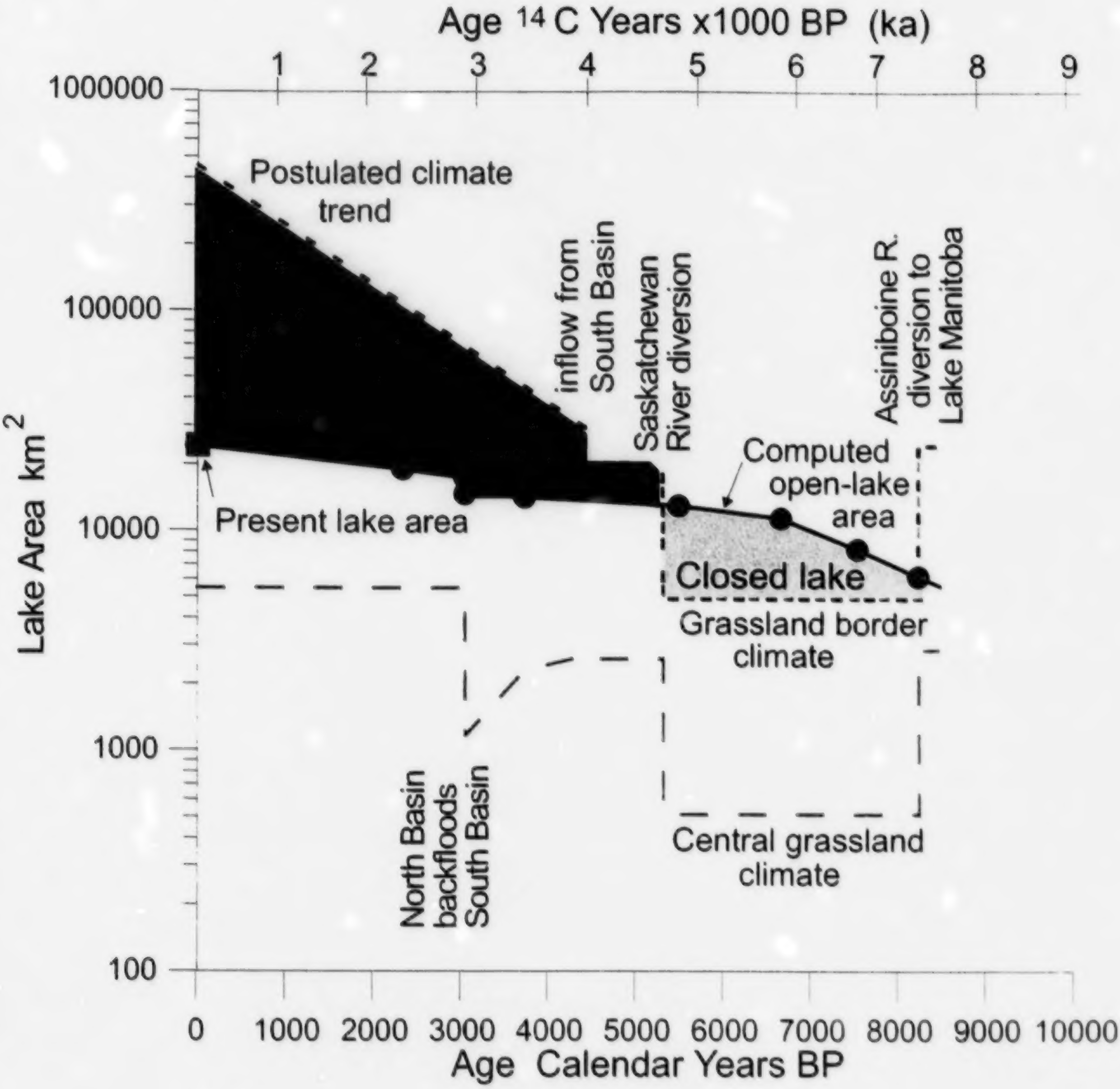


Figure 14. History of lake overflow status for the northern basin of Lake Winnipeg before 3060 cal BP (2.9 ka) and for all of Lake Winnipeg after 3060 cal BP (2.9 ka). The black square on the Y-axis marks the present area of Lake Winnipeg. See text for discussion.

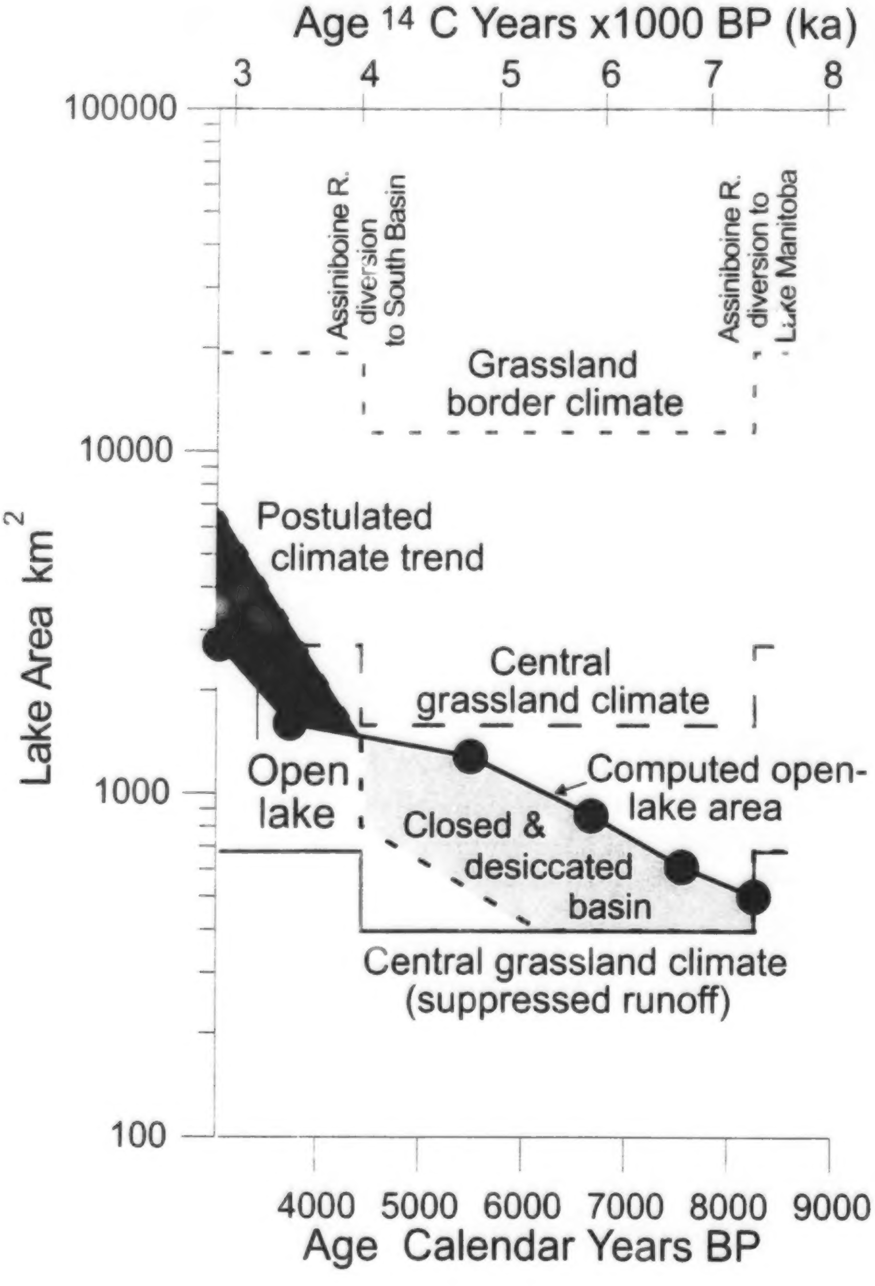


Figure 15. History of lake overflow status for the southern basin of Lake Winnipeg until 3060 cal BP (2.9 ka). See text for discussion.

6.2 Lake Winnipeg sediment physical properties - *Namao* 96-900

K. Jarrett

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17 Hawthorn Street, Dartmouth, Nova Scotia B2Y 2Y4

INTRODUCTION

Sediment physical property measurements provide information that aid in the characterization and correlation of lithologic units, construction of composite stratigraphic sections, correlation of lithology with geophysical records and in the interpretation of seismic reflection data.

K & K Geoscience was contracted by C.F.M. Lewis of GSC-Atlantic to obtain, process and compile sediment physical property data from gravity and piston cores collected in Lake Winnipeg. These cores were collected on the CCGS *Namao* 96900 cruise in August 1996. Core processing took place at the GSC-Atlantic Core Laboratory at Bedford Institute of Oceanography (BIO).

Sediment physical property measurements were taken on whole round core sections using the Multi-Sensor Track (MST). These measurements included compressional wave velocity, bulk density and magnetic susceptibility. Sediment physical property measurements and subsamples obtained from the split core included spectral reflectance, undrained shear strength, discrete bulk density and water content.

CORE PROCESSING

Laboratory procedure

The initial step in processing the 96900 Lake Winnipeg cores was non-destructive whole core x-ray using the GSC-Atlantic x-ray system. The whole core was then brought up to ambient room temperature and run through the MST for the measurement of sediment physical properties at a down-core resolution of 1 cm. The sediment physical properties measured by the MST include magnetic susceptibility, compressional wave velocity and bulk density.

Following whole core analysis, whole round samples were taken for consolidation testing. The core liner was split using the GSC-Atlantic splitter and the sediment was split longitudinally by pulling a piece of fine wire through the sediment along the cuts in the plastic core liner. The archive and working halves of the core were temporarily covered with plastic film to prevent pore water loss. The plastic core liner was labeled and meter tape was placed along the length of the core. The archive halves of the cores were scraped gently to expose a smooth fresh surface and were photographed with colour film at overlapping intervals of approximately 35 cm. The archive halves were then measured for spectral reflectance using a Minolta Spectrophotometer CM-2002 at 5 cm intervals, where possible. The archive halves of the core were then described.

The working halves of selected cores were immediately measured for shear strength at 10 cm intervals, dependant on core quality. The measurements were made using either a motorized miniature shear vane, a hand held pocket penetrometer or a hand held torvane. Discrete constant volume samples were taken to determine bulk density and water content of the sediment. Further subsampling for grain size, macro fossils, diatoms, ostracods, pore water and geochemical analysis was then completed. The working and archive halves were re-covered with plastic film, sealed in labeled plastic core sleeving, placed in labeled plastic d-tubes and stored in the GSC-Atlantic refrigerated storage unit.

A summary of x-ray data and physical property data available for each core is given in Table 1.

METHODS

X-ray

Whole core x-ray was used for the evaluation of core quality and semi-quantitative assessment of sediment structure and composition. A downcore x-ray image was stored on videotape as the core was moved and rotated at a constant rate.

Multi Sensor Track (MST)

The MST comprises a conveyor system, a central unit assembly, a microprocessor and a PC computer. The conveyor system consists of two track sections, mounted and aligned on either side of the central unit, and a 1.54 m core boat which is driven in either direction by a stepper motor and gear box assembly.

The central unit assembly incorporates a compressional wave (p-wave) logger, a gamma ray attenuation logger and a magnetic susceptibility loop. The p-wave logger system is located at the right hand end of the unit. The gamma ray attenuation logger and magnetic susceptibility loop are offset to the left of the p-wave logger at 14 and 48 cm respectively.

Each core section was placed in the core boat to the right of the p-wave logger and travelled incrementally past the p-wave logger, gamma ray attenuation logger and through the magnetic susceptibility coil. After each increment of travel readings from each sensor were taken.

A piece of plastic core liner filled with distilled water was run through the MST every four sections of core as a quality check of the MST system.

The quality of the bulk density and velocity values are dependent on: 1) an accurate measure of sediment thickness; 2) degree of sediment saturation; and 3) the absence of air voids between sediment and plastic core liner.

Compressional Wave Velocity

The p-wave logger system consists of two spring loaded compressional wave transducers (PWT) and two rectilinear displacement transducers attached to the PWT mountings. The PWT's are located on either side of the core and are easily moved to accommodate cores of varying diameter. Each PWT comprises a thickness mode 500 kHz piezoelectric crystal mounted in epoxy resin and housed in a stainless steel cylinder. A filled epoxy resin backing is used to shape the transmitted pulse. A short 500 kHz compressional wave pulse is produced at the transmitting transducer at a repetition rate of 1 kHz. This wave pulse travels through the core and is detected by the receiving transducer and the time of flight of the wave pulse is measured. The two rectilinear displacement transducers measure the displacement of the active faces of the PWT transducers from a known standard. Using this measured distance and knowing the thickness of the core liner the diameter of the sediment core can be calculated assuming that the core liner is full of sediment. The p-wave travel time is corrected for the P-wave travel time delay caused by the core liner and the electronics of the system.

Gamma Ray Attenuation

The gamma ray attenuation unit comprises a 10 millicurie Cesium-137 capsule (housed in a 150 mm diameter primary lead shield with a 6 mm collimator) and a sodium iodide scintillation detector (housed in a 100 mm diameter collimated lead shielding to minimize any background radiation). The source and detector are mounted on either side of the core. A narrow (pencil size) beam of gamma rays with energies principally at 0.662 MeV is emitted from the Cesium -137 source and passes through the diameter of the sediment core. At these energy levels Compton scattering is the primary mechanism for the attenuation of the gamma rays in most sedimentary material. The incident photons are scattered by collision with electrons encountered in the core and there is a partial energy loss. This attenuated gamma beam is measured by the sodium iodide detector. The Compton scattering of the photons is directly related to the number of electrons in the path of the gamma ray beam. The uncorrected bulk density of the core is calculated by comparing the attenuation of gamma rays through the whole core to the attenuation of the gamma rays through an aluminum standard. The aluminum standard consists of four different thicknesses of aluminum in an empty piece of plastic core liner of the same type used in the coring.

Magnetic Susceptibility

The magnetic susceptibility Bartington loop sensor (MS2B) is mounted to minimize the effects of magnetic or metallic components of the MST system. A low intensity non-saturating, alternating magnetic field is produced by an oscillator circuit in the sensor loop. Changes in the oscillator frequency caused by material that has a magnetic susceptibility is measured and converted into magnetic susceptibility values (CGS volume units).

Spectral Reflectance

High-accuracy measurements of spectral reflectance of the core, at wavelengths from 400 to 700 nm, were made using the Minolta Spectrophotometer CM-2002. A white standard is used to calibrate the system at regular intervals. The spectral reflectance values were used to calculate L* a* b*, referred to as the CIELAB system. L*, a* and b* are coordinates in 3 dimensional space containing all colours. The value of L* represents lightness, which equals zero for black and 100 for white. The a* value represents the amount of red (+) or green (-). The b* value represents the amount of yellow (+) or blue (-). Munsell colour values were also calculated from the spectral reflectance values.

Shear Vane

Undrained shear strength measurements were made using the GSC-Atlantic automated Wykeham-Farrance vane shear device following Boyce's procedures (1976). The vane rotation rate was 89 °/min. The vane has a 1:1 blade ratio with a dimension of 1.27 cm. The mini vane shear test provides an estimate of strength and a means of comparing downcore measurements. Measurements were not made in sections of core that were disturbed or that contained sand. A hand held Soiltest pocket penetrometer was used to measure the strength of the stiffer clay. A hand held torvane was used on the first cores tested until the automated shear vane device was available.

Constant volume sampling

A stainless steel cylinder of known volume was gently pushed into the core sediment at a constant rate. The cylinder was then carefully removed from the core and trimmed using a wire saw. The sediment was extruded from the cylinder, weighed, dried at 105° C for 24 hrs and weighed again. Bulk density and water content values were calculated using these measurements.

MST DATA PROCESSING

The raw MST data files were processed using the MST BIO6 version of the Futurebasic processing program.

Corrected p-wave travel time and calculated core thickness are used to calculate the uncorrected compressional wave velocity of the sediment. The uncorrected velocity is corrected to in situ temperature and pressure assuming a bottom water temperature of 4° centigrade and using the water depth at the core location.

Uncorrected bulk density is calculated using the calibration values obtained from the aluminum standard and the calculated core thickness. This uncorrected bulk density is then corrected for the presence of hydrogen in the pore water (Boyce, 1976). The final bulk density value is obtained by correcting for any density offset of the distilled water standard. The constant volume bulk density values are plotted at the same scale and are used as a check of the data.

The final bulk density value and an assumed grain density are used to calculate porosity.

DATA COMPILATION

The MST, spectral reflectance, shear strength, and constant volume data for individual cores were compiled as Excel 5.0 workbooks. Each workbook consists of individual worksheets containing the original physical property data sets and a worksheet of the compiled physical property data set.

The raw data files, processed data files and final Excel data files and Kaleidagraph plot files are shown in Appendix 10.3.

The compiled data set was imported into Kaleidagraph 3.0 where poor quality velocity and density data were masked. Unmasked (good quality) MST, shear strength and L*a*b* were plotted using Kaleidagraph 3.0. Two sets of MST, shear strength and L*a*b* plots were produced. One set (Part 1, Appendix 10.3) was plotted at varying scales to best illustrate downcore variations of the individual cores. Section break, porosity, constant volume density and water content data accompany the plots in Part 1. The second set (Part 2, Appendix 10.3) was plotted at the same scales to best compare all downcore sediment physical property data collected in Lake Winnipeg.

The shear strength and constant volume data were summarized and compiled as tables (Part 3, Appendix 10.3).

ACKNOWLEDGMENTS

The core processing team included D. Dwyer, D.L. Forbes, K. Jarrett, C.F.M. Lewis, E. Nielsen, L.H. Thorleifson, and B. Todd.

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Table 1 96900 Physical Property Data summary

Site Information	X-ray - video	X-ray - hard copy	MST	Shear Strength	Constant Volume	Consolidation Sample	Spectro - photometer	Grain Size	Comments
201 gc Gravity Core Water depth : 12.95 m Core Length : 1.92 m	X	X	X	X	X		X	X	
201 pc Piston Core Water depth : 12.95 m Core Length : 5.25 m	X	X	X	X	X		X	X	Cutter 5.04 - 5.25 m Pocket Penetrometer
202 gc Gravity Core Water depth : 13.63 m Core Length : 1.35 m	X	X	X		X		X	X	
202 pc Piston Core Water depth : 13.63 m Core Length : 5.89 m	X	X	X	X	X	X	X	X	Consolidation sample 5.53 - 5.68 m Torvane and shear vane
203 gc Gravity Core Water depth : 16.46 m Core Length : 1.64 m	X	X	X	X	X		X	X	Torvane
203 pc Piston Core Water depth : 16.46 m Core Length : 5.825 m	X	X	X	X	X		X	X	Torvane and shear vane
204 gc Gravity Core Water depth : 15.85 m Core Length : 1.72 m	X	X	X	X	X		X		Shear vane
204 pc Piston Core Water depth : 15.85 m Core Length : 5.79 m	X	X	X	X	X		X	X	Cutter 5.53 - 5.79 m Shear vane
205 gc Gravity Core Water depth : 15.85 m Core Length : 1.62 m	X	X	X	X	X		X	X	Shear vane
205 pc Piston Core Water depth : 15.85 m Core Length : 5.37 m	X	X	X	X	X		X	X	Cutter 5.18 - 5.37 m Shear vane

Table 1 96900 Physical Property Data summary

Site Information	X-ray - video	X-ray - hard copy	MST	Shear Strength	Constant Volume	Consolidation Sample	Spectro - photometer	Grain Size	Comments
206 gc Gravity Core Water depth : **15.85 m** Core Length : **1.68 m**	X	X	X	X	X		X		Shear vane
206 pc Piston Core Water depth : **15.85 m** Core Length : **4.69 m**	X	X	X	X	X		X	X	Cutter 4.50 - 4.69 m Shear vane
207 gc Gravity Core Water depth : **17.07 m** Core Length : **1.74 m**	X	X	X		X		X	X	
207 pc Piston Core Water depth : **17.07 m** Core Length : **3.44 m**	X	X	X		X	X	X		Cutter 3.27 - 3.44 m Consolidation sample 3.13 - 3.27 m
208 gc Gravity Core Water depth : **15.85 m** Core Length : **1.65 m**	X	X	X		X		X		
208 pc Piston Core Water depth : **15.85 m** Core Length : **2.44 m**	X	X	X		X		X	X	
209 gc Gravity Core Water depth : **16.46 m** Core Length : **1.73 m**	X	X	X		X		X		
209 pc Piston Core Water depth : **16.46 m** Core Length : **1.65 m**	X	X	X		X		X	X	Cutter 1.45 - 1.65 m
210 g Grab Sample Water depth : **15.85 m** Core Length :									
211 g Grab Sample Water depth : **15.85 m** Core Length :									

Table 1 96900 Physical Property Data summary

Site Information	X-ray - video	X-ray - hard copy	MST	Shear Strength	Constant Volume	Consolidation Sample	Spectro - photometer	Grain Size	Comments
217 pc Piston Core Water depth : **11.13 m** Core Length : **3.10 m**	X	X	X		X		X	X	Cutter 2.94 - 3.10 m
218 pc Piston Core Water depth : **10.36 m** Core Length : **1.39 m**	X	X	X		X		X	X	
219 gc Gravity Core Water depth : **10.52 m** Core Length : **1.19 m**	X	X	X		X		X	X	
219 pc Piston Core Water depth : **10.52 m** Core Length : **4.39 m**	X	X	X		X		X	X	
220 gc Gravity Core Water depth : **10.52 m** Core Length : **1.54 m**	X	X	X		X		X	X	
220 pc Piston Core Water depth : **10.52 m** Core Length : **5.53 m**	X	X	X		X		X	X	
221 gc Gravity Core Water depth : **10.36 m** Core Length : **1.37 m**	X	X	X	X	X		X		Shear vane
221 pc Piston Core Water depth : **10.36 m** Core Length : **5.78 m**	X	X	X	X	X		X	X	Cutter 5.59 - 5.78 m Shear Vane
222 gc Gravity Core Water depth : **10.36 m** Core Length : **1.46 m**	X	X	X	X	X		X	X	Shear vane
222 pc Piston Core Water depth : **10.36 m** Core Length : **7.86 m**	X	X	X	X	X	X	X	X	Consolidation sample 7.55 - 7.75 m Shear vane

Table 1 96900 Physical Property Data summary

Site Information	X-ray - video	X-ray - hard copy	MST	Shear Strength	Constant Volume	Consolidation Sample	Spectro - photometer	Grain Size	Comments
212 gc Gravity Core Water depth : 10.97 m Core Length : 1.53 m	X	X	X		X		X	X	
213 gc Gravity Core Water depth : 11.89 m Core Length : 1.61 m	X	X	X		X		X		
213 pc Piston Core Water depth : 11.89 m Core Length : 1.43 m	X	X	X	X	X		X		Pocket Penetrometer
214 gc Gravity Core Water depth : 11.28 m Core Length : 1.74 m	X	X	X		X		X		
214 pc Piston Core Water depth : 11.28 m Core Length : 4.33 m	X	X	X	X	X		X	X	Pocket Penetrometer
215 gc Gravity Core Water depth : 11.58 m Core Length : 1.73 m	X	X	X		X		X	X	
215 pc Piston Core Water depth : 11.58 m Core Length : 4.85 m	X	X	X	X	X		X	X	Cutter 4.70 - 4.85 m Pocket Penetrometer
216 gc Gravity Core Water depth : 11.89 m Core Length : 1.13 m	X	X	X	X	X		X	X	
216 pc Piston Core Water depth : 11.89 m Core Length : 4.75 m	X	X	X		X		X	X	
217 gc Gravity Core Water depth : 11.13 m Core Length : 1.09 m	X	X	X		X		X	X	

Table 1 96900 Physical Property Data summary

Site Information	X-ray - video	X-ray - hard copy	MST	Shear Strength	Constant Volume	Consolidation Sample	Spectro - photometer	Grain Size	Comments
223 gc **Gravity Core** Water depth : **9.75 m** Core Length : **1.55 m**	X	X	X	X	X		X	X	Shear vane
223 pc **Piston Core** Water depth : **9.75 m** Core Length : **7.39 m**	X	X	X	X	X		X	X	Shear vane
224 gc **Gravity Core** Water depth : **8.53 m** Core Length : **1.43 m**	X	X	X		X		X	X	
224 pc **Piston Core** Water depth : **8.53 m** Core Length : **7.31 m**	X	X	X		X		X	X	

6.3 Composition and texture of Lake Winnipeg cores

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INTRODUCTION

In the second phase of coring lake floor sediment in Lake Winnipeg in 1996, an attempt was made to collect a complete section through the Lake Agassiz sequence in the North Basin. Sites were chosen based on the seismic records (Todd, this volume) and a composite stratigraphic sequence was proposed using core segments from both the 1994 and 1996 cores (Lewis *et al.*, this volume). The validity of the proposed section was tested using physical properties such as whole core magnetic susceptibility, bulk density, acoustic compressional wave velocity, undrained shear strength and digital colour reflectance (Jarrett, this volume). This paper presents the results of compositional and textural parameters determined on those portions of the 1996 cores which complete the proposed Lake Agassiz sequence. For the most part, analytical methods were consistent with those used for the 1994 cores and grab samples (Last, 1996; Henderson, 1996).

SAMPLING AND ANALYTICAL METHODS

Those portions of the cores determined as representing part of the complete Lake Agassiz sequence in the North Basin were sampled for textural and compositional analyses. These included core 204 (interval from 530-570 cm depth), core 205 (15-535 cm) and core 206 (80-460cm), for a total of 50 samples (Lewis *et al.*, this volume). For 1996 cores, a 20 cm subsampling interval was used as opposed to the 10 cm interval used for 1994 cores.

The samples provided were analyzed for the following physical, mineralogical and geochemical parameters: detailed textural analysis, bulk mineralogy, major and trace metal geochemistry, and organic carbon and carbonate content. Carbonate determinations and particle size analyses were performed at the sedimentology laboratories of the Geological Survey of Canada, mineralogical analyses at the University of Manitoba and geochemical analyses at Chemex Inc, Mississauga, Ontario.

Textural Analysis

Particle size and textural data for both the 1994 and 1996 cores were determined using the Galai 2010 PSA automated particle size analyzer, but at different laboratories. A complete description of the methodology is presented in Last (1996). For this report, data were obtained for grain diameters ranging from 2 mm to <1 micron, where possible. Grain size subdivisions are consistent with those used for the 1994 cores:

Clay:	<4 microns diameter
Silt:	4 to 63 microns diameter
Sand:	63 microns to 2 mm diameter

Bulk Mineralogy

As with the 1994 samples, all mineralogical analyses of the 1996 core subsamples were conducted at the University of Manitoba laboratory using identical techniques (Last, 1996). Qualitative and quantitative mineralogical analysis of bulk sediment were determined by x-ray diffractometry (XRD).

Major and Trace Element Geochemistry

Geochemical analyses of both the 1994 and 1996 core subsamples were conducted at the laboratories of Chemex Inc. using identical techniques (Henderson, 1996). Approximately 1 gm of the bulk sediment was analyzed after a total leach (nitric-perchloric-hydrofluoric) using inductively coupled plasma-atomic emission spectrometry (ICP-AES) for most elements. Ag and Pb concentrations were determined by AAS (atomic absorption spectrophotometry); As by AAS following nitric-aqua-regia partial digestion.

Analytical precision and accuracy were monitored with laboratory standards and duplicate analyses. Results for the 1996 samples show good internal precision although accuracy is poor for some elements, particularly Ba, Cu, Mn, Ni, P and Pb.

Organic Carbon and Carbonate Content

The organic and non-organic carbon and carbonate content of bulk sediment samples were determined using the Leco CR412 Carbon Determinator. Carbonate percentages are based on the measurement of CO_2 produced by burning two sample portions of equal weight: one untreated, the other treated with dilute HCl. The fraction of inorganic carbon (non-carbonate) and calcium carbonate (or equivalent) in each sample is calculated. This method does not differentiate between biogenic and lithogenic carbonate. Because the methodology is significantly different from that used to determine the % organic matter and total carbonate mineral content of the 1994 samples (see Last, 1996), results are incomparable.

RESULTS

Appendix 10.8 provides a summary of the quantitative data obtained from the sampled intervals in the 1996 cores. Indicated on the first table (Table 1) are a sequence number, site identifier, sampling mid-point depth in cm below the top of the core and the results of textural analysis. The histograms and cumulative curves for particle size results are not included. Table 2 includes normalized percentages for quartz, K-feldspar, plagioclase, amphibole, clay minerals, calcite, high-Mg calcite, protodolomite, dolomite, monohydrocalcite, aragonite, magnesite, Na-sulphate, anhydrite, gypsum and pyrite, as well as the percent magnesium in calcite, magnesium in high-Mg calcite, and calcium in protodolomite. Table 3 includes the results of geochemical analysis for the following elements: Ag, Al, Ba, Be, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Sr, Ti, V, W, Zn and As. Table 4 presents the results of the organic and inorganic carbon content by the Leco Carbon Determinator and the calculated calcium carbonate equivalent.

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6.4 Sources of lead in Holocene Lake Winnipeg sediments: evidence from stable lead isotopic abundances

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ABSTRACT

Stable lead isotope composition can yield information on sources of lead in lake sediments. In this reconnaissance study, stable lead isotopic compositions were determined for nitric acid-soluble and residual sediment fractions of sediment samples from a north-south transect of Lake Winnipeg. Results show that lead in Lake Winnipeg sediment is derived from natural as well as anthropogenic sources and both interbasinal and vertical variations in source material can be distinguished. The natural-source lead in Lake Winnipeg sediments is predominantly derived from the Superior Province (model age 2.5 Ga). The North Basin sediment is characterized by highly radiogenic acid-soluble lead and relatively non-radiogenic residual lead derived from high radiogenic lead/common lead Archean granitic rocks of the Superior Province. Lead in the South Basin sediments is largely derived from Paleozoic and Mesozoic sedimentary rocks; these sediments have a more radiogenic common lead component originally extracted from the Superior Province during deposition of the Paleozoic and Mesozoic rocks. Vertical variations in lead isotope composition indicate three phases of lead input in Lake Winnipeg: 1) highly radiogenic Lake Agassiz sedimentation, 2) relatively constant isotopic compositions of natural Lake Winnipeg sources, and 3) reduced isotopic ratios of acid-soluble anthropogenic lead. Specific sources of anthropogenic lead for Lake Winnipeg can not be determined with the present data since the anthropogenic isotopic composition is unknown.

INTRODUCTION

Lake Winnipeg is the eleventh largest lake in the world. Covering a surface area larger than Lake Ontario and only slightly smaller than Lake Erie, it is an important feature of the Canadian landscape. It is an integral part of the Nelson River drainage basin which extends from the Rocky Mountains to Hudson Bay. The lake is situated over the contact between the Archean Superior Province to the east, and Paleozoic carbonates and siliciclastics of the Williston Basin to the west (Fig. 1) and is the largest of a group of lakes, including Lake Winnipegosis and Lake Manitoba, which are remnants of post-glacial Lake Agassiz. A constriction referred to as The Narrows divides the lake into two basins, the large North Basin (approximately 240 km by 100 km) and smaller South Basin (approximately 90 km by 40 km). These basins have relatively flat and shallow lakebeds with water depths averaging 9 m in the South Basin and 16 m in the North Basin (Canadian Hydrographic Service, 1981).

Seismostratigraphic analysis of the Lake Winnipeg Basin reveals that Paleozoic rock is truncated against a subsurface escarpment and generally buried by several metres of Holocene sediment (Todd et al., 1998). Two sequences are recognized within the Holocene sediments: the thick Lake Agassiz sequence (tens of metres thick) overlain unconformably by a thinner Lake Winnipeg sequence (from none to several metres thick). The lower sequence is characterized by firm, brownish grey to olive grey, silty clay rhythmites and banded silty clay with a few dropstones and grit (Lewis and Todd, 1996). This sequence is interpreted as deposition in glacial Lake Agassiz, with the rhythmites resulting from seasonal variations. The upper sequence, which overlies an erosional contact (Agassiz Unconformity), is characterized by soft, dark olive grey, silt-clay mud with discontinuous bands of lighter grey mud and sand grains near the base. This sequence is the result of accumulation in modern Lake Winnipeg.

The water budget of Lake Winnipeg is supported by inflows from four major river systems: the Winnipeg River (mean monthly flow of 771 m^3s^{-1}), Saskatchewan River (mean monthly flow of 667 m^3s^{-1}), Red-Assiniboine rivers (mean monthly flow of 159 m^3s^{-1}), and Dauphin River (mean monthly flow of 57 m^3s^{-1}) and numerous other streams surrounding the lake (Lewis and Todd, 1996). Except for the Winnipeg River, which drains from the Superior Province, these major rivers drain areas of urbanization and agricultural activity to the south and west of the lake (Kling, 1996). The catchment of the latter three rivers encompasses the Paleozoic and Mesozoic sedimentary terrains of central Canada and the north central United States. Outflow from Lake Winnipeg is through the Nelson River at the north end of the lake.

Despite its importance as a recreational and commercial resource, there has been a paucity of research on Lake Winnipeg. Other than limited limnological and land-based studies, the only major scientific effort was a chemical, physical and biological survey involving the collection of fifty bottom sediment grab samples and several short cores by the Freshwater Institute of Fisheries and Oceans Canada in 1969 (Kling, 1996; Brunskill and Graham, 1979). Due to the need for an enhanced understanding of the regional geological history, a multidisciplinary offshore survey of Lake Winnipeg was performed in 1994 by the Geological Survey of Canada (GSC) and Manitoba Energy and Mines (MEM).

As part of this comprehensive study, the lead isotopic composition of the Holocene sediments was examined. The aim of this reconnaissance study was to document spatial, temporal and compositional variations in the stable lead isotopic signatures. In the past, lead isotopes measured from sediment, vegetation, water and air samples have been used to identify natural and anthropogenic sources and to trace fluxes of lead contamination (Sturges and Barrie, 1987, 1989; Flegal et al., 1989; Bacon et al., 1996; Farmer et al., 1996) Some of the more recent studies of sediment samples (Gobeil et al., 1995; Graney et al., 1995) have used a sequential extraction technique to determine the isotopic signature of lead in various sediment fractions. This information was then used to distinguish between natural and industrial lead sources. The present research uses a similar approach to examine the origins of lead in Lake Winnipeg. This geologically unique location, overlying the boundary between Archean and Paleozoic bedrock, makes it possible to assess the influence of these two distinctly different sources on the isotopic composition of the lake sediments. In addition, more recent sediments were examined for evidence of anthropogenic lead sources.

LEAD ISOTOPES

There are four naturally occurring stable lead isotopes: ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb. Only ^{204}Pb is non-radiogenic and thus, can be treated as a reference isotope; the remaining three isotopes are daughter products of radioactive decay of ^{238}U, ^{235}U and ^{232}Th (Faure, 1986).

Stable lead isotopic ratios depend on the age and original mineral composition of the source rock from which the lead is derived (Sturges and Barrie, 1989). Since ^{204}Pb is not derived from radioactive decay its abundance has not changed since the Earth formed; however, radioactive decay of U and Th has continually produced ^{206}Pb, ^{207}Pb, and ^{208}Pb. Consequently, not only has the abundance of lead increased, but the isotopic composition of average Earth lead has become more enriched in the radiogenic isotopes through geologic time. Isotopic ratios are usually expressed as ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb but in environmental work ^{206}Pb/^{207}Pb is commonly used.

Common rocks, such as granites, contain minerals with sufficiently high U/Pb and Th/Pb ratios to cause measurable changes in their lead isotopic compositions over time. The lead isotopic ratios of these rocks will continue to evolve until the lead is removed from the U-, Th-bearing system; thus, lead extracted from very old granitic rock will have a more radiogenic isotopic composition than lead removed from the system early in the rock history. Other rocks and minerals, such as galena or K-feldspar, have such low U/Pb and Th/Pb ratios that their lead isotopic composition does not change appreciably since the time of formation. Such lead, in which the isotopic composition has not significantly changed by in situ generation of radiogenic lead (^{206}Pb,^{207}Pb and ^{208}Pb), is termed common lead. Although U/Pb and Th/Pb ratios are altered by radioactive decay, a number of geologic processes can also significantly fractionate these elements, including magma generation, metamorphism and weathering. These geologic processes may produce regional variations in the U/Pb and Th/Pb ratios that affect the isotopic evolution of lead.

Lead in lake sediments is derived from natural sources, such as mineral weathering and erosion, volcanic emissions and soil dust, and in more recent times from anthropogenic emissions, primarily smelting, iron and steel manufacture, fossil fuel combustion, and the release of municipal and industrial effluents (Nriagu and Pacyna, 1988; Pacyna et al., 1991; Gobeil et al., 1995). Although pre-industrial anthropogenic sources have been documented (Renberg et al., 1994) most contributions have occurred since the mid-nineteenth century with combustion of leaded gasoline being the most significant (Graney et al., 1995).

A wide variety of studies, including surveys of sediments from the St. Lawrence Estuary and the Great Lakes (Gobiel et al., 1995; Graney et al., 1995), aerosols from the Great Lakes and rural Eastern Canada (Sturges and Barrie, 1987; 1989), and water samples from coastal regions of British Columbia and the Great Lakes (Stukas and Wong, 1981; Flegal et al., 1989) have used stable lead isotopic ratios to trace the origin of anthropogenic lead inputs. This is possible because the isotopic ratios of lead are not fractionated by normal chemical and physical processes; lead released to the environment retains the isotopic composition of the source from which it was derived (Sturges and Barrie, 1989). This approach has generally been successful in identifying local sources of pollution. Sturges and Barrie (1987) suggested that the observed differences in ^{206}Pb/^{207}Pb ratios from urban Canada and the United States are the result of the different isotopic compositions of the lead used by Canadian and American companies in producing their leaded gasoline.

MATERIALS AND METHODS

Several gravity/piston cores and box cores were collected from Lake Winnipeg during a GSC cruise (designated *Namao* 94-900) in August 1994. Following core recovery the gravity/piston core liners were cut in 1.5 m sections, sealed and stored upright in a core cooler. Box cores were subsampled using a vacuum pump to force a 10 cm core liner into the sediment; the short cores were then subdivided into 1cm slices aboard ship. The box core samples were collected in order to determine trace metal content and isotopic composition, thus great care was taken to avoid contamination, especially from atmospheric sources.

Three box cores (approximately 40 cm in length) and two gravity cores (Core 103 = 816 cm and Core 122a = 472 cm in length) were sampled for stable lead isotope analysis (Fig. 1). Selection of one gravity core and one box core from each basin and an additional box core from The Narrows provides a north-south transect of Lake Winnipeg. Box cores were subsampled at sediment depths of 1, 12, 28 and 40 cm and gravity cores were subsampled at 120 cm intervals, providing a total of 24 samples.

In order to investigate sources of lead input to sediments of Lake Winnipeg a procedure was needed to extract the labile component from the total lead. Sequential chemical extractions have been developed for partitioning trace metal components into five fractions operationally defined as: exchangeable, carbonate-bound, Mn and Fe oxide-bound, bound to organic matter and residual (Tessier et al., 1979). However, since the majority of lead in the freshwater environment, including the anthropogenic component, is associated with organic matter through bioaccumulation or adsorption by humic substances (Jaworski, 1987), a simpler method of extraction was chosen. A dilute acid leach dissolves lead bound to organic material and ferromanganese oxides leaving the residual lead bound to the mineral structure (Shirahata et al., 1980). Graney et al. (1995) tested several acid leaches and found negligible differences in concentrations and isotopic ratios obtained from lead extracted by various HCl and/or HNO_3 strengths. For the present study 3 N HNO_3 was chosen.

All sample preparation was done in a laminar flow fume hood in a clean lab. Approximately 100 mg of air-dried sample was mixed with 4 ml of 3N HNO_3 in a 15 ml Teflon beaker and warmed on a hot plate for 15 minutes. The capped beakers were then placed in an ultrasonic bath for 30 minutes to aid disaggregation of clay-rich sediments. After several hours the solvent was separated from the residual sediment using a micropipette, and dried in a Teflon beaker. The residue was rinsed with water (twice) to remove any remaining solvent then dissolved in a series of strong acids: 0.5 ml 12N HNO_3 and 2 ml HF; 2 ml 8N HNO_3; then 2 ml 6N HCl. The lead was separated from other elements by a sequential HCl-HBr ion-exchange column with AG-1-X8 anion exchange resin. Blanks for laboratory procedures are typically less than 100 pg and therefore are negligible. Isotopic ratios were measured on a Finnigan-MAT 261 multicollector thermal ionization mass spectrometer using a single Re filament and silica gel and phosphoric acid. The measured ratios were corrected for fractionation; the correction factors (Table 1) were determined by repeated analysis of the NBS 981 standard.

RESULTS AND DISCUSSION

Bedrock geology around Lake Winnipeg varies significantly from east to west in both rock type and age (Fig. 1). The rates and products of erosion differ according to the rock type, affecting the concentration and isotopic composition of lead incorporated into the lake sediments. Granites and granitic gneisses are enriched in U, Th and Pb (3.5-4.8, 12.9-21.5 and 19.6-23.0 average values, respectively) while carbonates (1.9, 1.2 and 5.6 average values, respectively) and siliciclastics (1.4-3.2, 3.9-11.7 and 13.7-22.8 average values, respectively) contain lower concentrations of these elements (Faure, 1986); thus the old silica-rich rocks of the Superior Province have a greater potential to enrich the sediments with lead than do the Paleozoic sedimentary rocks to the west. This high availability of lead in the Precambrian rocks, however, is balanced by the slow rates of erosion and low sediment loads carried by rivers draining shield areas (Brunskill and Graham, 1979).

The majority of the sediment deposited in Lake Winnipeg is derived from till and glaciolacustrine material surrounding the lake (Henderson and Last, 1998). These surficial sediments reflect the composition of the underlying bedrock. On the east side of Lake Winnipeg a veneer of non-calcareous till overlies Precambrian bedrock (Nielsen and Thorleifson, 1996). These tills have relatively high mean concentrations of trace elements including Pb (Henderson and Last, 1998). To the south and west of Lake Winnipeg glacial sediments (till and glaciolacustrine deposits) are derived from underlying Paleozoic carbonates and Cretaceous shales. These sediments are characterized by moderate to high carbonate content and low concentrations of trace elements such as Pb (Henderson and Last, 1998).

Bulk sediment lead concentrations of core and grab samples from Lake Winnipeg reveal a north to south increase in the amount of lead (Henderson, 1996; Lockhart, 1996). In addition, there is a general increase in lead concentration up core. The lead enrichment of surface samples in the South Basin has been attributed to anthropogenic input (Henderson, 1996); however, this fails to explain lead spikes that occur downcore (e.g. 115 cm or 405 cm in Core 122A and 715 cm in Core 103). Postdepositional remobilization and redistribution of lead in lacustrine sediments is believed to represent only a small proportion (< 4%) of the total lead abundance (Gobeil and Silverberg, 1989). Thus, the north to south trend is probably the result of variations in sediment source and drainage systems feeding the two basins.

The North Basin is supplied by the Saskatchewan and Dauphin Rivers to the west and numerous small rivers to the east. Both of the western rivers flow through extensive lake systems before they reach Lake Winnipeg; for example, much of the sediment load from the Saskatchewan River is deposited in Cedar and Moose lakes (Brunskill and Graham, 1979). Retention of lead is virtually complete due to the high particle reactivity of this element (Blais and Kalff, 1993). Thus most of the lead carried by the large western rivers probably never reaches Lake Winnipeg; instead, much of the North Basin sediment is derived from shoreline erosion. The South Basin receives most of its input from the Red-Assiniboine and Winnipeg rivers; neither of these flow through lake systems. The Winnipeg River drains the Precambrian terrane to the east of the lake, however, under normal conditions, its sediment load is insignificant (Brunskill and Graham, 1979). The majority of the sediment load in the South Basin is deposited in Lake Winnipeg by the Red-Assiniboine river system; much of the material carried by the Red-Assiniboine River is derived from glaciolacustrine deposits rich in Cretaceous clay minerals (Henderson and Last, 1998).

The stable lead isotope ratios (reported as ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb and ^{206}Pb/^{207}Pb) of acid-soluble lead and the residual sediment measured in this study are presented in Table 2 and Figures 2 and 3. When the isotopic ratios ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb are plotted against ^{206}Pb/^{204}Pb, the points essentially fall on a straight line (Fig. 2). This line represents the mixing line of acid-soluble and residual sediment samples. Generally the residual sediment samples cluster at the end of the mixing line with low radiogenic lead values while the acid-soluble leads produce a more dispersed group of more radiogenic values.

In Lake Winnipeg sediments, acid-soluble lead is much more radiogenic than residual lead (Table 2 and Figures 2 and 3) suggesting that radiogenic lead is preferentially weathered as a result of partial decomposition of the source material. The isotopic composition of lead derived from complete rock dissolution would reflect the U/Th/Pb abundances of the original minerals and subsequent radioactive decay of Th and U. However, leaching experiments on metamict mineral phases revealed preferential release of radiogenic lead from radiation-damaged sites (Gariépy et al., 1990). Stern et al.(1966) estimated that up to 85% of the radiogenic lead was lost as a result of chemical weathering of zircons from gneiss. Work by Hart and Tilton (1966) on sediments from Lake Superior illustrated that the lead isotopic compositions of the acid leach and water leach fractions were more radiogenic than the lead in the bulk sediment (Table 3). An investigation of the lead isotopic composition of a mountain stream draining granodiorite bedrock in California illustrated that the lead isotope ratios in the stream water were much more radiogenic than those measured for the whole rock. This was interpreted as preferential weathering of U-rich minerals such as apatite (Erel et al., 1991). This preferential weathering from radiation-damaged sites and/or U-rich minerals incorporates radiogenic lead into the acid-soluble component while depleting the residual component.

Within the residual lead fraction, the four samples from Core 113b cluster in a small group distinct from the other residual lead samples. On a ^{206}Pb/^{204}Pb - ^{208}Pb/^{204}Pb plot for the residual fraction (Fig. 4), Core 113b samples exhibit a different slope (m = 1.97) than the remaining samples (m = 1.03). This perhaps indicates the influence of a localized sediment source from the small stream draining the Superior Province to the southeast. Core 113b is the only core taken in close proximity to shore and therefore, the location most likely to experience the influence of a local source. A localized Superior Province sediment source is also consistent with the low ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb ratios observed in Core 113b residual sediments (Fig. 4) since the lead contained in the residual component is probably common lead characteristic of the Precambrian. Isotopic ratios (^{206}Pb/^{204}Pb - ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb -^{208}Pb/^{204}Pb) for the acid-soluble lead fraction of Core 113b samples are colinear with other acid-soluble lead samples (Fig. 2), thus this component appears to be less likely influenced by localized lead sources. This is to be expected due to the fact that the acid-soluble fraction represents the more labile portion of lead (Graney et al., 1995).

Pending completion of lead concentration measurements for acid-soluble and residual fractions the assumption was made that the abundance of lead in the acid-soluble component is greater than that of the residual component. This assumption is quite reasonable based on concentration measurements of sequential extraction components made by other workers (Tessier et al., 1979; Graney et al., 1995). Both acid-soluble and residual lead lies along a straight line in coordinates of ^{206}Pb/^{204}Pb - ^{207}Pb/^{204}Pb; in view of the unequal allotment of lead this may be due to unleached acid-soluble lead contamination of the residual lead component. Thus any departure of the residual fraction from a straight-line trend could be masked by the unleached portion of acid-soluble lead. However, isotopic compositions of the residual lead exhibit consistent changes from sample to sample but do not reflect changes in the acid-soluble lead (Table 2, Fig. 3). Therefore, this is probably not a significant problem.

It is more likely that lead in the residual and acid-soluble components of all samples were originally derived from the same source rocks. The slope of the regression line ($m = 0.165$) from the plots of the ^{206}Pb/^{204}Pb - ^{207}Pb/^{204}Pb data indicates a model age of the original source rock of 2.5 Ga (Faure, 1986), thus suggesting the lead in Lake Winnipeg sediments is predominantly derived from the Superior Province. This regression line intersects the Stacey-Krammers Model growth curve at 2.5 Ga (Fig. 5). The Stacey-Kramers Model predicts the isotopic evolution of average crustal lead. Since the mixing line from the ^{206}Pb/^{204}Pb - ^{207}Pb/^{204}Pb plot intersects the growth curve at 2.5 Ga, the model age of the original source rock, the original source represented average crustal lead at that time.

Isotopic ratios suggest that the acid-soluble lead tends to be more radiogenic towards the north (Fig. 3; Table 2). As discussed earlier, the concentration of lead is lower in the North Basin than in the South Basin; this is presumed to be due to lack of lead input from the major rivers to the west. If this is the case then the majority of lead comes from shoreline erosion and small rivers draining Shield rocks to the east; thus, the sediments of the North Basin would be strongly influenced by Archean bedrock and bedrock derived till. The isotopic compositions of acid-soluble lead in cores 103 and 108 are comparable with acid leach results of Quaternary lake sediments from other Canadian Shield localities, suggesting that the Precambrian source material has a strong influence on the isotopic ratios (Table 3; Chow, 1965; Hart and Tilton, 1966; Doe, 1970).

The mineralogy and age of these source materials suggest that the small amount of sediment derived from these resistant rocks would be enriched in radiogenic lead. Growth curves of lead in average continental crust indicate that the ^{206}Pb/^{204}Pb ratio of common lead in Superior Province (Archean) rocks should have values of about 13 to 13.5 (Faure, 1986). However, Superior Province rocks are dominated by granites and gneisses which generally have higher U/Pb and Th/Pb ratios than the Paleozoic carbonates and siliciclastics. Since Superior rocks are very old, the ratio of radiogenic lead/common lead for these Archean rocks is relatively high; consequently, lead extracted from the Superior Province today would have a highly radiogenic isotopic composition.

In the South Basin the source of lead becomes dominated by the sediment load of the Red-Assiniboine River; this river system draws its sediment supply from Paleozoic and Mesozoic carbonates and siliciclastics. The Winnipeg River supplies a negligible amount of sediment to the South Basin for although its annual discharge is 4 to 10 times greater than the Red River, the sediment load is reduced due to its Precambrian shield watershed (Brunskill and Graham, 1979). Since carbonates and siliciclastics generally have lower U/Pb and Th/Pb ratios (Faure, 1986) and the rocks are much younger, it is likely that less radiogenic lead has been produced in these rocks since deposition; consequently the ratio of radiogenic lead/common lead is lower. Thus, the isotopic composition of acid-soluble lead in the South Basin has a less radiogenic signature than the acid-soluble lead of the North Basin.

The isotopic ratios of residual lead shows the opposite trend to that of the acid-soluble lead; residual lead of the South Basin is characterized by higher ^{206}Pb/^{207}Pb ratio than that of the North Basin. In Paleozoic rocks, the common lead isotopic composition is more radiogenic with ^{206}Pb/^{204}Pb values of about 17.5 to 18. This high ratio common lead component is not preferentially weathered from the Paleozoic rock as the radiogenic lead is preferentially extracted. Thus the residual lead components tend to reflect the composition of the common lead component.

Vertical variations in the stable lead isotope signatures can be used to divide the core into sections: the Lake Agassiz, the lower Lake Winnipeg and the anthropogenic-influenced sections (Fig. 3). The lowermost section, corresponding to the post-glacial Lake Agassiz sequence, is based on two samples, one at 720 cm from Core 103 of the North Basin and one at 460 cm from Core 122a of the South Basin. From these limited data, the Lake Agassiz sediments appear to be characterized by lead which is more radiogenic than the Lake Winnipeg sequence within the same core. This may indicate a short-lived increase in the supply of Precambrian sediment immediately following deglaciation. The Wisconsinan ice sheets eroded and entrained large amounts of material as they advanced across the Precambrian Shield and after ice retreat this sediment was released resulting in large volumes of unconsolidated Precambrian detritus being deposited in Lake Agassiz (Klassen, 1983).

The lower Lake Winnipeg sediments are characterized by relatively constant lead isotope compositions at each location (Fig. 3). These isotopic signatures represent the natural post-Agassiz source of lead to Lake Winnipeg sediments and indicates that these sources remained virtually unchanged for several thousand years.

In the most recent Lake Winnipeg sediments the isotopic ratio of acid-soluble lead is significantly reduced relative to older sediments within the same core, with the possible exception of Core 103 in the North Basin (Fig. 3). This reduction in isotopic ratios is interpreted as the result of the addition of lead from anthropogenic sources. Prior to the advent of unleaded gasoline, the dominant source of anthropogenic lead emissions was the combustion of gasoline, contributing up to 76% of total anthropogenic lead (Pacyna et al., 1991). ^{206}Pb/^{207}Pb ratios for typical leaded gasolines range from 1.06 to 1.20 (Chow and Johnstone, 1965; Farmer et al., 1996). These ratios are significantly lower than the natural post-Agassiz lead sources thus supporting the contention that the decrease in the content of radiogenic lead in the acid-soluble lead in upper samples is due to additions of anthropogenic lead. In addition to the lead input derived from leaded gasoline, there are probably influences from industrial sources associated with mining and smelting and municipal effluent. For example, lead extracted from Flin Flon, Manitoba, is characterized by an average ^{206}Pb/^{207}Pb ratio of 1.01 (Sturges and Barrie, 1987). Further, the contribution of lead from natural sources has been affected by changes in erosion patterns as a result of agriculture, forestry, construction and forest fires. The specific anthropogenic sources responsible for the lead isotope composition of the uppermost sediments cannot be determined from the available data. The acid-soluble component consists of lead from natural and anthropogenic sources in unknown proportions; therefore, the precise isotopic composition of the anthropogenic lead is not known.

The possible anthropogenic influence is quite evident in the upper two samples (1 and 12 cm) in each box core and in the surface sample of Core 122a; however, it is not apparent in the surface sample of Core 103 where there is only a slight reduction in the isotopic ratios. The time frame of this anthropogenic input is consistent with the distribution of ^{210}Pb. ^{210}Pb (half-life 22.4 years) is a radioactive decay product of radon gas (^{222}Rn). It is deposited from the atmosphere and once incorporated into the sediment its activity decreases as a function of time (Dörr et al., 1991). The limit for ^{210}Pb activity is about 150 years (Lockhart, 1996). The detection of ^{210}Pb at 5 and 15 cm in Core 122a but only in the top 5 cm in Core 103 suggests that these three samples were deposited less than 150 years ago (Lockhart, 1996).

Pollen diagrams from southwest Manitoba and Kouert Lake, Minnesota show an increase in weed pollen such as Ambrosia (ragweed) pollen and Chenopodiineae in the upper 30-50 cm of lake sediment (Ritchie and Yarranton, 1978; McAndrews, 1988). The increased abundance of these particular weed pollen is associated with early European settlement in south central Canada and usually indicates the start of anthropogenic perturbation of the sediment record. The marked decrease in the ^{206}Pb/^{207}Pb ratios in the uppermost sediments in the box cores corresponds to changes observed in the distribution of indicator pollen.

CONCLUSIONS

This study demonstrates that lead of Lake Winnipeg sediment is derived from natural as well as anthropogenic sources. The natural-source lead in Lake Winnipeg sediments is predominantly derived from the Superior Province (model age 2.5 Ga); however, interbasinal variations in isotopic composition of acid-soluble and residual components indicate that some lead experienced a complex depositional history. The North Basin receives much of its lead directly from high radiogenic lead/common lead rocks of the Superior Province.

These sediments are characterized by a highly radiogenic acid-soluble lead component and a relatively less-radiogenic residual lead. In the South Basin sediment, lead is largely derived from Paleozoic and Mesozoic carbonates and siliciclastics with low radiogenic lead/common lead ratios. The common lead component of the Paleozoic and Mesozoic rocks was originally extracted from Superior Province rocks then later eroded from these rocks and deposited in Lake Winnipeg sediment. As a result the residual sediment fraction of the South Basin is characterized by a more radiogenic lead isotopic composition.

Vertical variations in lead isotope composition of the acid-soluble component suggest the most recent sediments are strongly influenced by anthropogenic sources. These most recent sediments are characterized by a decrease in the content of radiogenic lead in the acid-soluble fraction. Specific sources of anthropogenic lead for Lake Winnipeg can not be determined with the present data since the extent of anthropogenic influence is unknown.

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Table 1: Correction factors determined by repeated analysis of the NBS 981 standard to compensate for machine fractionation of measured isotopic ratios.

$$206/204_{corr} = 206/204_{meas} + (206/204_{meas} \text{ X } 0.0027827)$$
$$207/204_{corr} = 207/204_{meas} + (207/204_{meas} \text{ X } 0.004148)$$
$$208/204_{corr} = 208/204_{meas} + (208/204_{meas} \text{ X } 0.0055887)$$

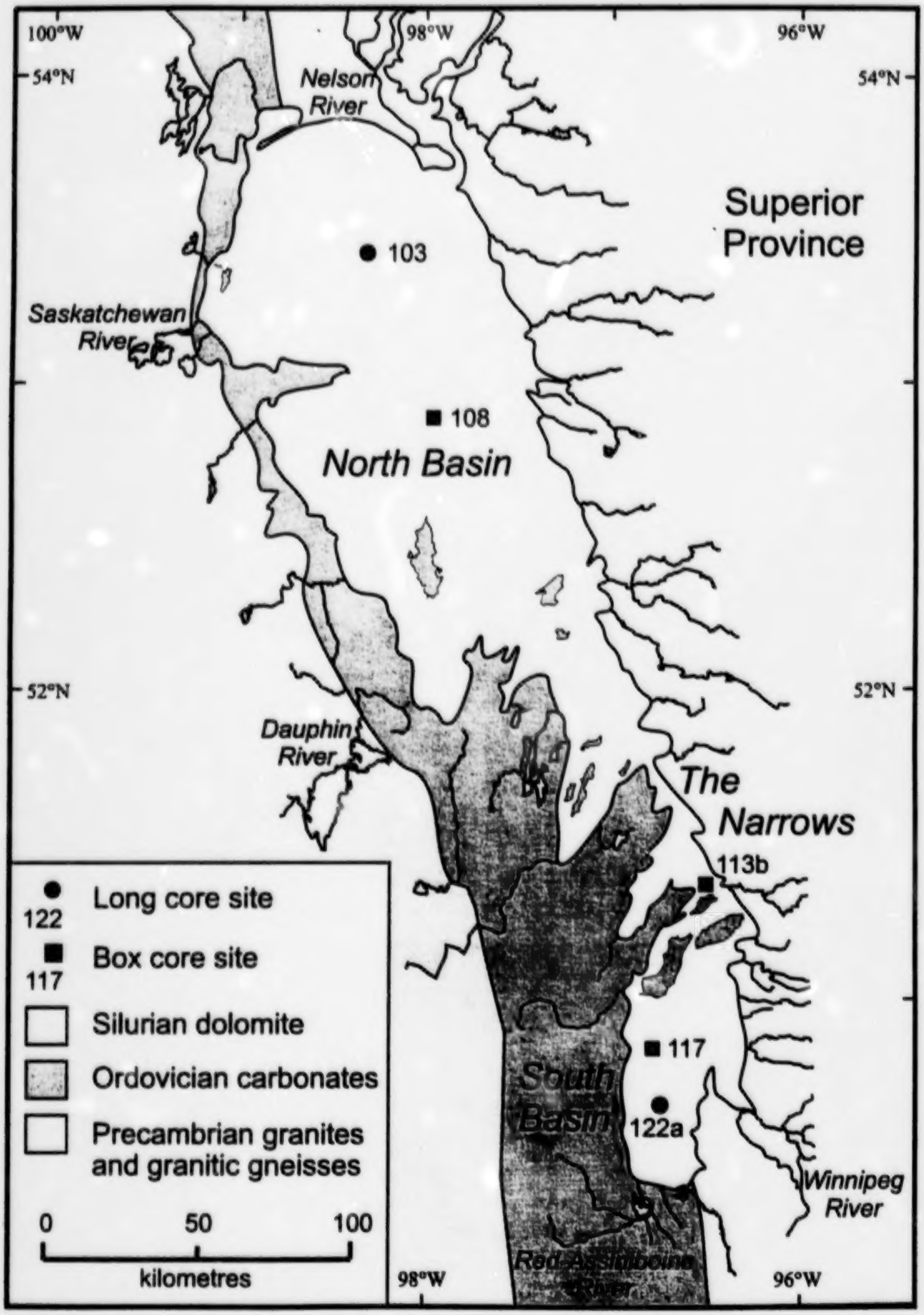
Table 2: Isotopic compositions of acid-soluble and residual lead.

	Acid-Soluble					Residual sediments				
	Sample	**$206/204_{corr}$**	**$207/204_{corr}$**	**$208/204_{corr}$**	**206/207**	**Sample**	**$206/204_{corr}$**	**$207/204_{corr}$**	**$208/204_{corr}$**	**206/207**
	Core 103					**Core 103**				
	0	23.90	16.42	43.46	1.46	0	18.16	15.45	38.01	1.18
	120	24.07	16.45	43.70	1.46	120	17.84	15.41	37.58	1.16
	240	24.31	16.47	43.85	1.48	240	17.85	15.41	37.65	1.16
	360	24.42	16.48	44.00	1.48	360	17.53	15.36	37.35	1.14
	480	24.43	16.47	44.01	1.48	480	17.39	15.34	37.24	1.13
North Basin	600	23.72	16.35	43.31	1.45	600	17.58	15.37	37.45	1.14
	720	25.17	16.45	44.85	1.53	720	18.47	15.53	38.28	1.19
	Core 108					**Core 108**				
	1	22.17	16.17	41.79	1.37	1	17.58	15.38	37.35	1.14
	12	23.45	16.42	43.17	1.43	12	17.60	15.36	37.38	1.15
	28	24.05	16.47	43.86	1.46	28	16.95	15.27	36.47	1.11
	40	24.17	16.51	43.88	1.46	40	17.75	15.50	37.72	1.14
	Core 113b					**Core 113b**				
	1	21.96	16.13	41.56	1.36	1	16.86	15.25	36.34	1.11
The Narrows	12	21.90	16.13	41.46	1.36	12	16.83	15.24	36.27	1.10
	28	22.78	16.24	42.34	1.40	28	16.78	15.23	36.22	1.10
	40	22.98	16.29	42.52	1.41	40	16.91	15.25	36.47	1.11
	Core 117					**Core 117**				
	1	20.38	15.88	40.05	1.28	1	18.30	15.50	38.05	1.18
	12	20.22	15.86	39.86	1.28	12	18.54	15.51	38.30	1.20
	28	21.33	16.01	41.01	1.33	28	18.51	15.52	38.26	1.19
	40	21.17	15.96	40.87	1.33	40	18.25	15.48	37.84	1.18
South Basin	**Core 122a**					**Core 122a**				
	0	19.92	15.81	39.55	1.26	0	18.79	15.57	38.59	1.21
	120	20.98	15.94	40.60	1.32	120	18.77	15.56	38.55	1.21
	240	21.50	16.01	41.04	1.34	240	18.57	15.51	38.32	1.20
	360	21.79	16.05	41.29	1.36	360	18.47	15.51	38.28	1.19
	460	23.25	16.29	42.61	1.43	460	18.48	15.51	38.42	1.19

Table 3. Isotopic composition of lead in Quaternary lake sediments from adjacent drainage systems of the Canadian Shield.

Locality	Source	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Hudson Bay,	1,2	25.00	16.41	46.83
Canada	1,2	24.39	16.34	46.54
	1,2	24.15	16.28	45.90
	1,2	23.42	16.23	45.04
	1,2	23.49	16.35	45.01
	1,2	22.36	16.17	44.66
	1,2	22.07	16.12	42.71
	1,2	21.63	16.00	43.37
Great Slave	1,2	23.41	16.38	49.33
Lake, Canada	1,2	20.99	15.97	40.69
Great Bear	1,2	24.15	16.59	44.10
Lake, Canada	1,2	22.08	16.18	42.13
	1,2	21.56	16.13	41.77
	1,2	21.46	16.15	41.37
Lake Superior,	1,3	22.84	16.34	42.86
North America	1,3	22.48*	16.20*	42.34*
	1,3	20.53**	15.87**	40.34**

Most values represent acid-soluble lead components, those marked with asterisks represent samples which are not acid-soluble sediment fractions: * water-soluble leach, ** bulk sediment lead composition. Sources: 1. Doe, 1970; 2. Chow, 1965; 3. Hart and Tilton, 1966.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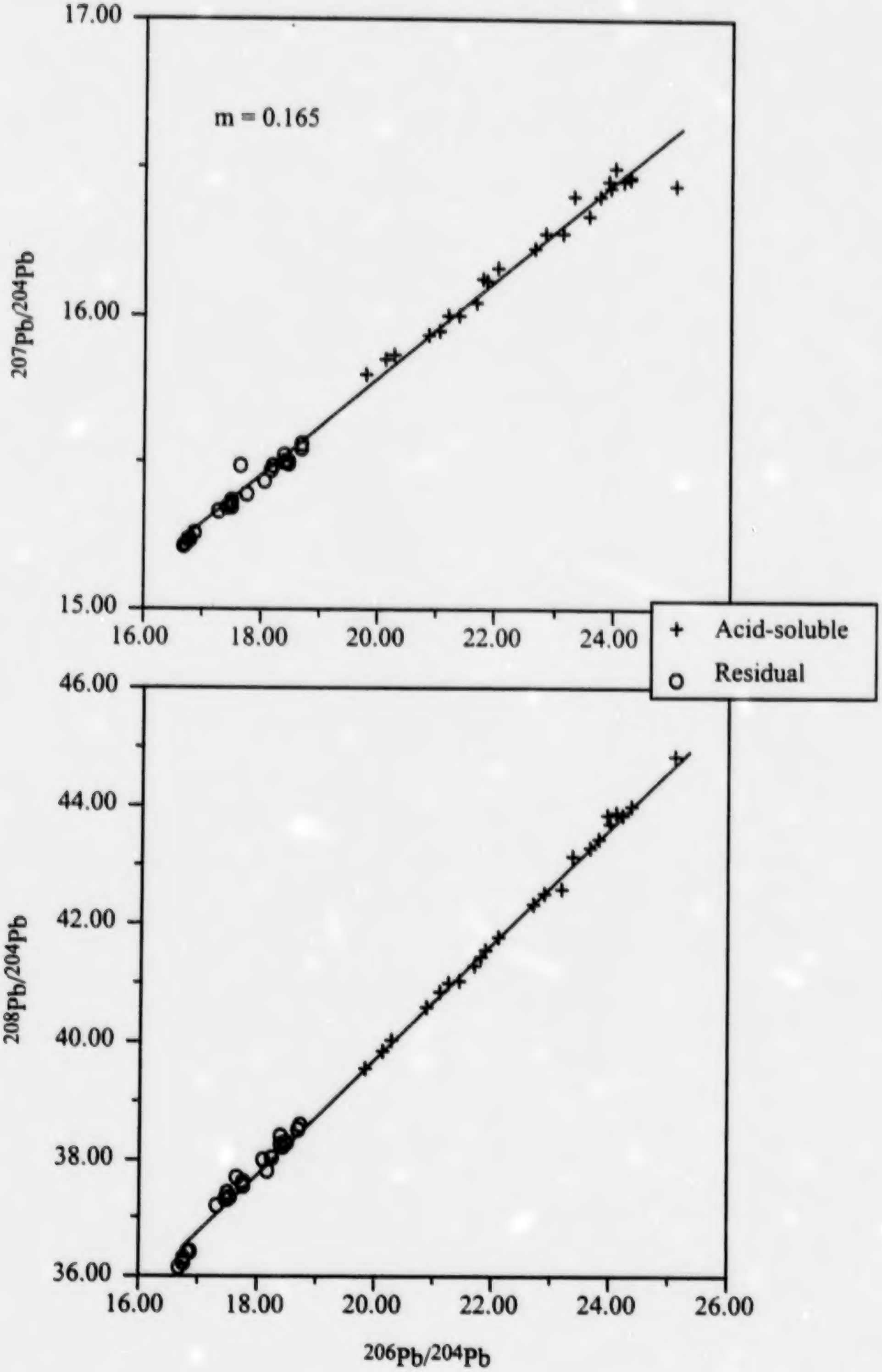
98°W
96°W
54°N
52°N
Nelson River
Saskatchewan River
Dauphin River
Superior Province
103
108
North Basin
The Narrows
113b
117
122a
South Basin
Winnipeg River
Red-Assiniboine River
Long core site
122
Box core site
117
Silurian dolomite
Ordovician carbonates
Precambrian granites and granitic gneisses
0
50
100
kilometres

Figure 1.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17.00
16.00
15.00
207Pb/204Pb
16.00
18.00
20.00
22.00
24.00
+ Acid-soluble
o Residual
46.00
44.00
42.00
40.00
38.00
36.00
208Pb/204Pb
16.00
18.00
20.00
22.00
24.00
26.00
206Pb/204Pb

Figure 2.

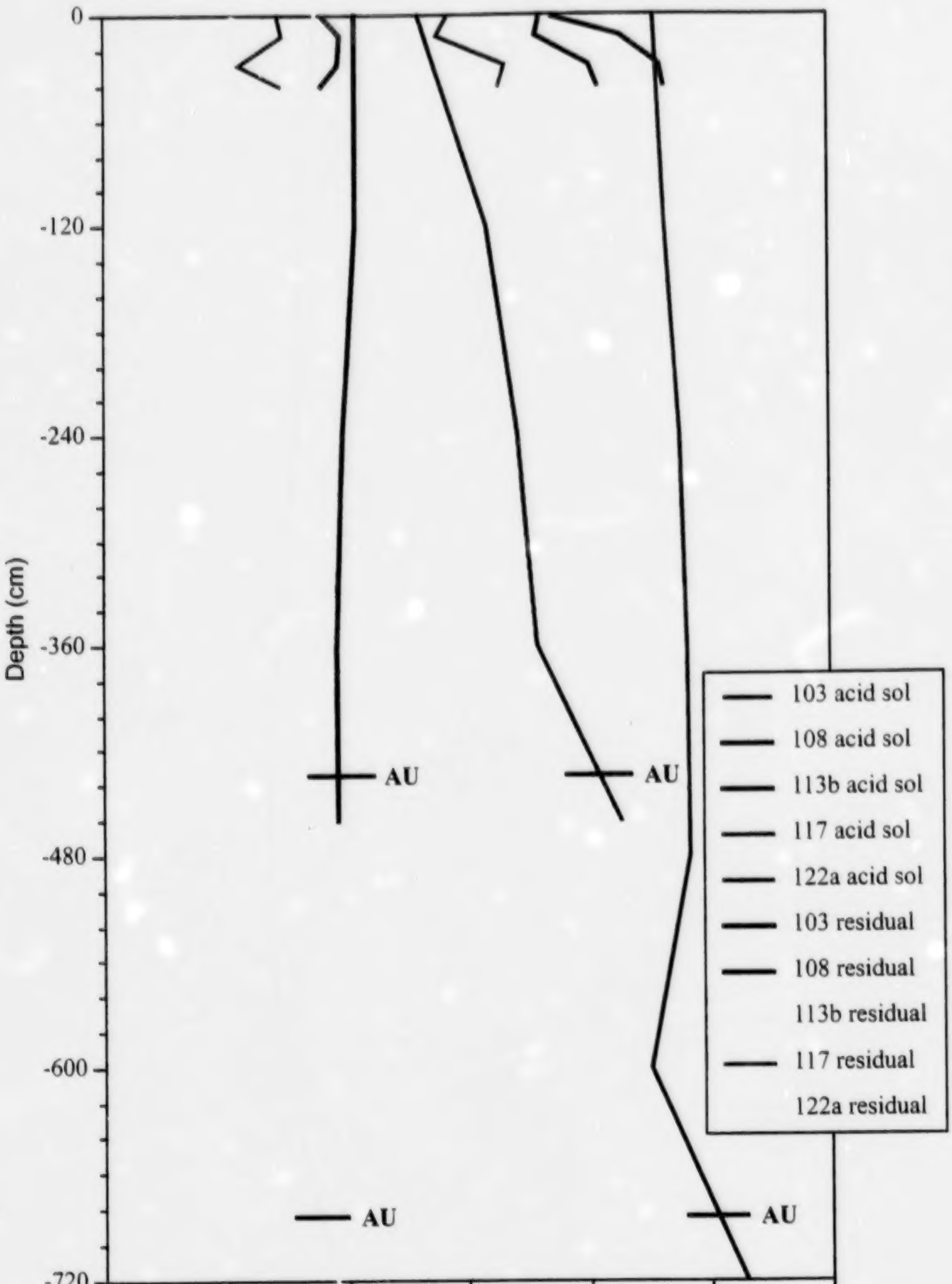
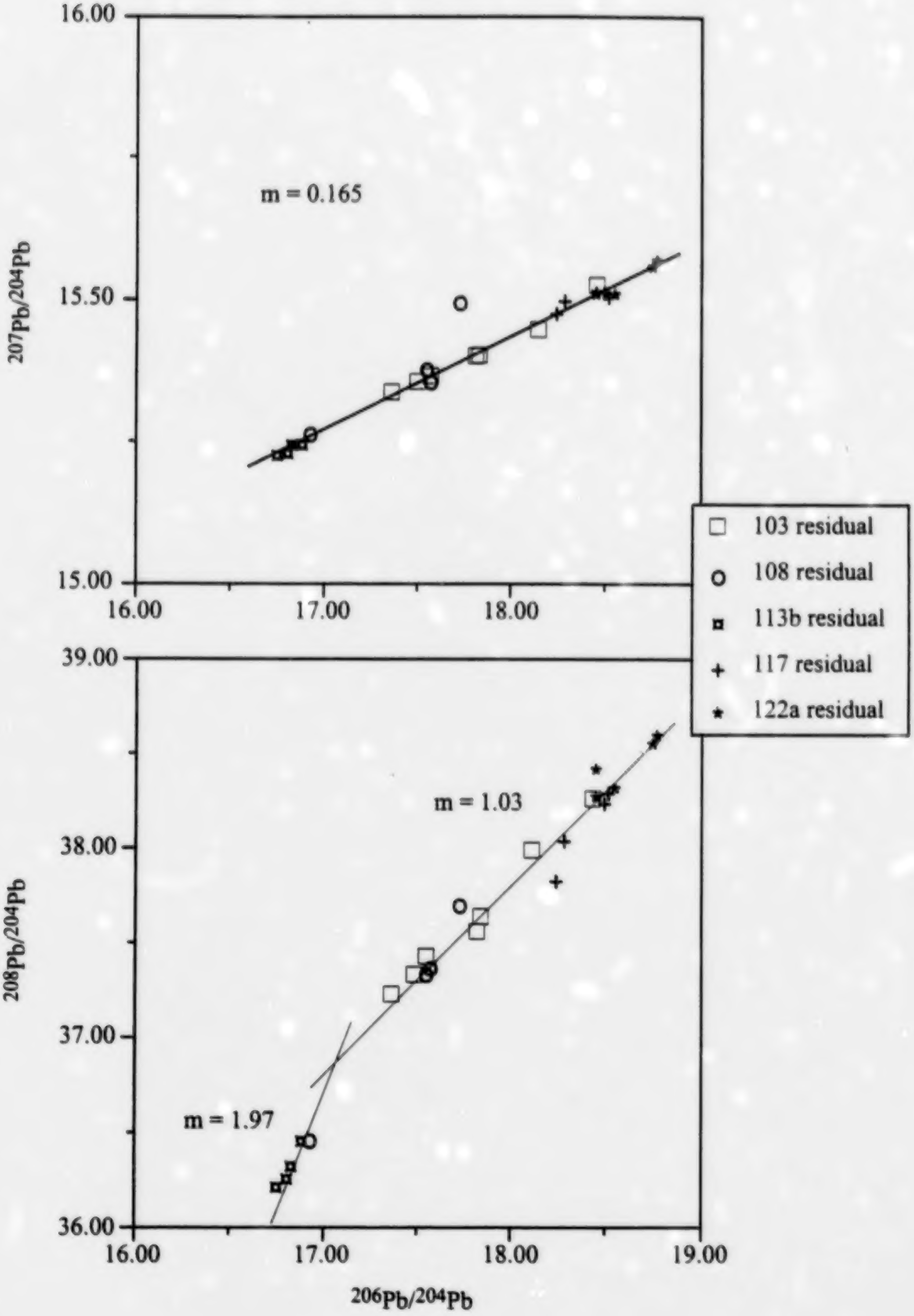

0
-120
-240
-360
-480
-600
-720
Depth (cm)
1
1.1
1.2
1.3
1.4
1.5
1.6
^{206}Pb /^{207} Pb
AU
AU
AU
AU
103 acid sol
108 acid sol
113b acid sol
117 acid sol
122a acid sol
103 residual
108 residual
113b residual
117 residual
122a residual

Figure 3.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15.50
15.00
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m = 0.165
16.00
17.00
18.00
39.00
38.00
37.00
36.00
$^{208}Pb/^{204}Pb$
m = 1.03
m = 1.97
16.00
17.00
18.00
19.00
$^{206}Pb/^{204}Pb$
□ 103 residual
○ 108 residual
¤ 113b residual
+ 117 residual
★ 122a residual

Figure 4.

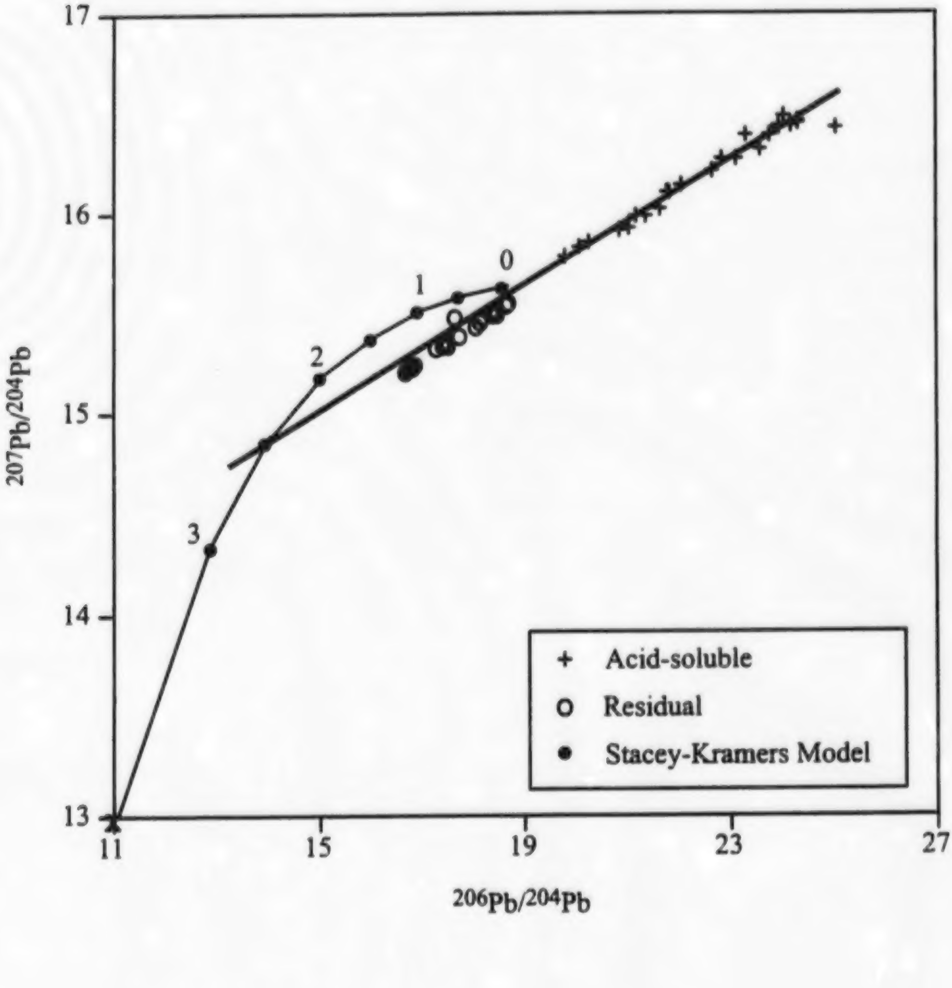
17
16
15
14
13
11
15
19
23
27
207Pb/204Pb
206Pb/204Pb
0
1
2
3
+ Acid-soluble
o Residual
● Stacey-Kramers Model

Figure 5.

7. Geochronology

7.1 Observations of Holocene paleomagnetic secular variation and rates of sedimentation in Lake Winnipeg

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INTRODUCTION

The Earth's magnetic field is a vector and can be completely characterized by three components at any point in space and time. The first component is declination, the angle of deviation between geographic north and magnetic north in the horizontal plane. The second component is inclination, the dip angle of the magnetic vector below the horizontal plane. The final component is the magnitude of the field or geomagnetic intensity. Geomagnetic secular variation (SV) is the "typical" temporal variation of the three components of the Earth's magnetic field between polarity transitions (reversals). The peak-to-trough amplitudes of North American secular variation features for the last 12,500 years are ≤ 40 degrees for inclination, ≤ 50 degrees for declination, and ≤ a 3-fold change in intensity (King et al., 1983a). Studies in North America indicate that secular variation patterns are reproducible on a regional scale of 3000-5000 km (King et al., 1983a; 1983b; Lund, 1996) and are very useful for stratigraphic correlation and dating of Holocene sediments.

HOLOCENE SV RECORDS

The most powerful approach to obtaining accurate age determinations from lake sediments is the multi-disciplinary use of SV, radiocarbon dating, and biostratigraphic studies. This paper reports the results of paleomagnetic SV, with a limited number of radiocarbon age determinations of plant macrofossils and ostracode valves (Telka, this volume), from box, gravity, and piston cores from seven sites located throughout Lake Winnipeg (Figure 1). Our approach is to correlate the inclination records from Lake Winnipeg cores to the radiocarbon dated inclination records from Fish Lake, Oregon (Verosub et al., 1986) and three Minnesota lakes — Elk Lake (Sprowl and Banerjee, 1989), Kylen Lake, and Lake St. Croix (Lund and Banerjee, 1985). These sites were selected because they have high quality SV records and are located relatively close to Lake Winnipeg (Fig. 2). We used the inclination records exclusively because declination records are more likely to be affected by wire-line coring problems (e.g. twisting) King et al. 1983a, and paleointensity records are significantly more difficult to obtain (King et al., 1983b). The inclination correlations are used to provide SV dates in conventional radiocarbon years for Lake Winnipeg sediments.

Lund (1996) identified a number of correlative SV features in the radiocarbon-dated inclination records (I1-I14) of these sites, which are shown in Figure 3. We added inclination features I0 and I9.5 to Lund's (1996) compilation of SV features. The radiocarbon ages of these features are summarized in Table 1. We follow Lund (1996) in accepting or rejecting the individual ages of inclination features from the four reference sites for use in calculating average ages. The average ages of the inclination features are then used to determine age models for Lake Winnipeg sediments.

SEDIMENTS AND MAJOR PROCESSES AFFECTING SEDIMENTATION IN THE LAKE WINNIPEG BASIN

The Holocene sediments deposited in Lake Winnipeg (the Winnipeg Sequence) rarely exceed 10 m in thickness and rest on a regional unconformity, the Agassiz Unconformity (Todd et al., 1996). The Agassiz Unconformity is the time-transgressive boundary between the Winnipeg Sequence and the thick underlying sediments (the Agassiz Sequence) deposited in glacial Lake Agassiz (Todd et al., 1996). The Agassiz Sequence has a maximum thickness of 50 m in the South Basin of Lake Winnipeg and a maximum thickness of over 100 m in the North Basin (Todd et al., 1996).

Initial results of the Lake Winnipeg project indicate that the Lake Winnipeg Basin has experienced Holocene regional tilting to the north-northeast caused by isostatic rebound following retreat and collapse of the Laurentide Ice Sheet (Todd et al., 1996). The uplift and tilting is the dominant control on lake level in Lake Winnipeg for overflowing conditions, and has caused a gradual, time - transgressive southward migration of the southern shore of Lake Winnipeg for thousands of years (Todd et al., 1996). In addition, superimposed on the long term control of lake level by regional tilt, are the effects of climate change and increased inflow due to the mid-Holocene diversion of the Saskatchewan River to Lake Winnipeg (Todd et al., 1996).

The major goals of the paleomagnetic SV studies are: (1) to determine the age of the basal sediments in the Winnipeg Sequence at each core site and thereby provide a minimum age estimate for the Agassiz Unconformity at these sites and a chronology for the development of Lake Winnipeg, and (2) determine the variation in sedimentation rate within the Winnipeg Sequence. In addition, we note the possibility of a relationship between paleoenvironmental changes in lake development, for example, rates of water-level rise, shore erosion, or river sediment inflow, and the observed variations in sedimentation rate.

METHODS

Paleomagnetic studies were done on archive halves of the Lake Winnipeg cores using a 2-G Enterprises Model 760 automated cryogenic magnetometer system. All measurements were done at a 2-cm interval. An initial natural remanent magnetization (NRM) was measured, and then the cores were remeasured after alternating-field (A.F.) demagnetization at 10.0, 15.0 and 20.0 mT.

The A.F. demagnetized inclination records of the individual box cores, gravity cores, and piston cores were correlated and a composite inclination versus depth record was constructed for each site. The individual records from seven Lake Winnipeg sites were compared and correlated to each other, and then the records were compared and correlated to the regional radiocarbon-dated inclination records shown in Figure 3. These correlations were used to determine age-versus-depth models for each Lake Winnipeg site and to estimate sedimentation rates for these sites.

A total of eight radiocarbon dates was used for comparison with the SV age dating (Table 2); these were selected from age determinations of macroscopic biological remains using the accelerator mass spectrometer (AMS) method (Telka, this volume).

RESULTS

Step-wise, whole-core, A.F. demagnetization indicates that minor secondary overprints are removed from Lake Winnipeg cores at relatively low peak fields. A typical example of the results of A.F. demagnetization at 10.0, 15.0 and 20.0 mT for Core PC203 from the North Basin of Lake Winnipeg is shown in Figure 4. The 10.0 mT A.F. demagnetization step typically removed 8-14% of the original natural remanent magnetization (NRM) intensity, whereas the 20.0 mT A.F. demagnetization step removed 25-35% of the NRM intensity. Minor changes in the inclination are generally observed between the original NRM and the 10.0 mT A.F. step, whereas almost no change was observed between the 10.0 mT, 15.0 mT, and 20.0 mT A.F. steps. The 20.0 mT A.F. demagnetized inclination results were used to derive SV ages for Lake Winnipeg sediments.

Several corers (box, gravity, and piston) were used to sample Lake Winnipeg sediments. At some sites all three corers were used. Typically the box core subcores and short gravity cores recover an undisturbed record of the upper 0.5 m of sediment, whereas the upper section (usually the upper 10-25 cm) of long gravity (> 2 m) and piston cores can be either disturbed, or missing entirely. On rare occasions, a long gravity corer or a piston corer which fails to trigger properly near the sediment-water interface may bypass soft sediments at the surface and within the sediment column to a cumulative maximum of 2-3 m. In this situation, the corer begins to core only when it encounters stiffer (slightly stronger) sediments.

We constructed composite depth scales for the multiple core types obtained at each site by assuming that the box-core SV record was undisturbed and by shifting the top of gravity and piston core records relative to the box-core record. The gravity and piston core records were shifted downward if it appeared that material was missing from the top of the section, whereas the records were shifted upward if the top of the record appeared to be "stretched", another common type of core disturbance. The adjustment of piston core 122 was done relative to piston core 223, which was obtained from a nearby location. Note that two interpretations of the SV record are possible for core 122. In one, in which the upper 3 inclination features are assumed missing, the 2.4 m shortening of the core relative to core 223 implies the upper 2.4 m of the sediment section is also missing. In the alternate interpretation, all inclination features are present and the shortening is distributed throughout the core length, attributed to intermittent sediment bypassing and/or compaction. The alternate interpretation is preferred for reasons stated below. The core adjustments are summarized in Table 3 except for the alternate interpretation of core 122.

SV AGE MODELS

North Basin Sites

Secular variation age models were obtained from four sites located in the North Basin of Lake Winnipeg (Fig. 1). A box core (BC101), a gravity core (GC201), and piston core (PC201) were obtained from a water depth of 12 m in the western North Basin (Fig. 1). The interpreted inclination records of these cores are shown in Figure 5. The age versus depth curves and the minimum age of the Agassiz Unconformity (AU) at this site (4460 years B.P.) are shown in Figure 6. The information shown in Figures 5 and 6 and the linear sedimentation rates (core depth interval/age difference for the interval) for the western North Basin site are summarized in Table 4.

A box core (BC102), a gravity core (GC203), and two piston cores (PC 203 and PC103) were obtained from a water depth of 16 m in the central North Basin (Fig. 1). The interpreted inclination records of these cores are shown in Figure 7. Note that inclination features 12 and 13 are interpreted to be absent because of missing sediment at the Agassiz Unconformity. The age-versus-depth curves and the age of the AU at this site (6960 years B.P.) are shown in Figure 8. The information shown in Figures 7 and 8 and the linear sedimentation rates for the central North Basin site are summarized in Table 5.

A gravity core (GC204) and a piston core (PC204) were obtained from a water depth of 16 m in northeastern North Basin (Fig. 1). The interpreted inclination records of these cores are shown in Figure 9. The age-versus-depth curves are shown in Figure 10. The information shown in Figures 9 and 10 and the linear sedimentation rates for the northeastern North Basin are summarized in Table 6.

A box core (BC110), a gravity core (GC214) and a piston core (PC214) were obtained from a water depth of ll m in the southern North Basin (Fig. 1). The interpreted inclination records of these cores are shown in Figure 11. The age-versus-depth curves and the age of the AU at this site (5430 years B.P.) are shown in Figure 12. The information shown in Figures 11 and 12 and the linear sedimentation rates for the site are summarized in Table 7.

The average linear sedimentation rates versus radiocarbon age for the North Basin sites are plotted in Figure 13. The average linear sedimentation rate is highest at the central North Basin site 203/103 (mean rate = 0.094 cm/year), whereas it is lowest at the southern North Basin site 214 (mean rate = 0.067 cm/year). Intermediate rates occur at the northeastern North Basin site 204 (mean rate = 0.075 cm/year) and the western North Basin site 201 (mean rate = 0.077 cm/year). The four North Basin sites show a similar pattern in the temporal variation of linear sedimentation rates. Intervals of slower rates are observed between 200-1300 years B.P., 2400-4000 years B.P., 5300-6400 years B.P., and 7600-8400 years B.P. (Fig. 13). On the other hand, intervals of higher rates are observed between 0-200 years B.P., 1300-2100 years B.P., 4000-5300 years B.P., and 6400-7000 years B.P.

South Basin Sites

Secular variation age models were obtained from three sites located in the South Basin of Lake Winnipeg. A box core (BC116), two gravity cores (GC223 and GC122), and a piston core (PC223) were obtained from a water depth of 10 m in the central South Basin (Fig. 1). The interpreted inclination records of these cores are shown in Figure 14. Note that alternate interpretations of the SV inclination record are possible for the long gravity core GC122. The second interpretation showing sediment recovery from surface to 472 cm is preferred. This interpretation is consistent with compositional trends in the core which show, for example, higher near-surface values for organic matter, silt and sand content, clay mineral abundance, and non-detrital carbonate mineral abundance in common with adjacent core PC223 and other Lake Winnipeg cores (Henderson and Last, 1998). The age-versus-depth curves and the SV age of the AU at this site (about 3850 years B.P.) are shown in Figure 15. The information shown in Figures 14 and 15 and the linear sedimentation rates for the central South Basin are summarized in Table 8.

A box core (BC117), a gravity core (GC222), and piston core (PC222) were obtained from a water depth of 10 m in the northwestern South Basin (Fig. 1). The interpreted inclination records of these sites are shown in Figure 16. The age versus depth curves and the age of the AU at this site (4060 years B.P.) are shown in Figure 17. The information shown in Figures 16 and 17 and the linear sedimentation rates for the northwestern South Basin site are summarized in Table 9.

A gravity core (GC217) and a piston core (PC217) were obtained from a water depth of 7 m in the northern South Basin (Fig. 1). The interpreted inclination records of these cores are shown in Figure 18. The age versus depth curves and the age of an upper unconformity at 132 cm (U) at this site (2980 years B.P.) are shown in Figure 19. A lower unconformity at 302 cm, thought to be the AU (Lewis et al., this volume), is undated. The information shown in Figures 18 and 19 and the linear sedimentation rates for the northern South Basin site are summarized in Table 10.

The average linear sedimentation rates versus radiocarbon age for sites in the South Basin is plotted in Figure 20, excluding the alternate interpretation for site 122. The average linear sedimentation rate is comparable at Sites 122/223 ,122 alternate, and 222 (about 0.17-0.18 cm/year), whereas it is one-fourth as high at Site 217 (0.043 cm/year). The linear sedimentation rate in the central South Basin is double the rate observed in the central North Basin. The three South Basin sites show a similar pattern in the temporal variation of linear sedimentation rates. Intervals of lower rates are observed between 0-1300 years B.P., 2100-2500 years B.P., and ~4000 years B.P. On the other hand, higher rates are observed between 1300-2100 years B.P. and at ~3300 years B.P. Similar temporal variation in sedimentation rates is observed in both the North and South Basins for the interval 0-2500 years B.P., with the exception of the recent (0-200 years) increase observed in the North Basin. The increase in sedimentation rates observed at 3300 years B.P. in the South Basin is not observed in the North Basin.

RADIOCARBON DATES

The paleomagnetic SV ages were compared with eight AMS radiocarbon dates obtained from macroscopic biological remains found within Lake Winnipeg sediments (Telka, this volume). The results are summarized in Table 11, and show reasonable agreement in the range of ±300-500 years for plant fossils. The one ostracode age compared is much older (>1000 years older), implying a relatively large reservoir age for this carbonate valve.

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Table 6. Depth of inclination features and sedimentation rates for site 204.

Table 7. Depth of inclination features and sedimentation rates for site 214.

Table 8a. Depth of inclination features and sedimentation rates for site 223/122.

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Figure 4. Downcore paleomagnetic inclination features (numbered) measured in core 96900-PC203, showing their stability at different levels of demagnetization.

Figure 5. Downcore paleomagnetic inclination features (numbered) measured in cores at site 201.

Figure 6. Age-depth curves (slope is sedimentation rate) for cores at site 201.

Figure 7. Downcore paleomagnetic inclination features (numbered) measured in cores at site 103 and 203.

Figure 8. Age-depth curves (slope is sedimentation rate) for cores at site 103/203.

Figure 9. Downcore paleomagnetic inclination features (numbered) measured in cores at site 204.

Figure 10. Age-depth curves (slope is sedimentation rate) for cores at site 204.

Figure 11. Downcore paleomagnetic inclination features (numbered) measured in cores at site 214.

Figure 12. Age-depth curves (slope is sedimentation rate) for cores at site 214.

Figure 13. Linear sedimentation rate versus radiocarbon age for cores in the North Basin of Lake Winnipeg.

Figure 14. Downcore paleomagnetic inclination features (numbered) measured in cores at site 223 and 122. An alternate interpretation of inclination features in 122 is shown by the italic numerals.

Figure 15. Age-depth curves (slope is sedimentation rate) for cores at site 223/122.

Figure 16. Downcore paleomagnetic inclination features (numbered) measured in cores at site 222.

Figure 17. Age-depth curves (slope is sedimentation rate) for cores at site 222.

Figure 18. Downcore paleomagnetic inclination features (numbered) measured in cores at site 217.

Figure 19. Age-depth curves (slope is sedimentation rate) for cores at site 217.

Figure 20. Linear sedimentation rate versus radiocarbon age for cores in the South Basin of Lake Winnipeg, not including the alternate interpretation for 122.

TABLE 1: Correlation and age estimates of inclination features in four radiocarbon-dated secular variation records from Western North America.

Inclination Feature	Fish Lake OR	±	Elk Lake MN	±	Lake St. Croix MN	±	Kylen Lake MN	±	AVERAGE AGE radiocarbon years	±
I0	*400*	*100*	200	100	250	100	—	—	225	120
I1	*1190*	*90*	870	120	960	90	—	—	915	130
I2	*1525*	*105*	1340	100	1310	140	—	—	1325	140
I3	*1915*	*65*	1525	100	1520	40	—	—	1523	90
I4	*2280*	*80*	1745	100	1675	85	—	—	1710	120
I5	*2585*	*85*	2090	190	2100	70	—	—	2095	170
I6	2870	90	2500	110	2530	130	—	—	2515	140
I7	3715	145	3250	350	3425	145	—	—	3338	330
I8	4200	180	3690	90	3915	195	3985	145	3948	260
I9	4635	105	4455	100	4385	135	4350	180	4456	190
I9.5	5400	120	5100	100	5500	120	5400	150	5350	200
I10	6300	130	*5820*	*70*	6315	95	6745	105	6453	260
I11	6685	155	*6225*	*220*	6710	60	6920	50	6772	160
I12	6855	155	6805	110	6955	65	7110	60	6931	170
I13	7530	115	*7795*	210	7740	330	7540	90	7651	260
I14	8225	115	*9005*	*200*	*9200*	*200*	8485	85	8355	190

Table 2:
Radiocarbon Dates from Lake Winnipeg Cores

LW Core	Interval (cm)	Fossils	Wt (mg)	CAMS#	AMS date
122	425-433	Scirpus seed (B. Vance)		17434	4040 ± 70
201	434-439	charred spruce needles (2 frags.)	0.6	35499	4800 ± 70
204	362-373	ostracodes	3.3-3.5	38676	6700 ± 80
204	513-518	spruce needle fragment (1)	0.9	38678	6750 ± 70
214	298-303	wood fragment (1)	1.7	38679	3630 ± 50
217	127-132	bulrush (Scirpus) seed (1 large)	3.9	35498	3340 ± 50
223	507-509	Scirpus sp. (large size) seed	4.8	34550	3280 ± 60
223	661-666	Scirpus sp. (large size) seed	5.3	34551	4000 ± 60

Table 3:
Depth Adjustments (cm) for Lake Winnipeg Core Correlations

SITE	GRAVITY CORE	PISTON CORE
103	N/A	0
122	N/A	+ 240
201	+10	+ 5
203	0	+ 12
204	0	+20
214	0	-10
217	0	0
222	-10	0
223	+25	+ 20

(+) : shifted down
(-) : shifted up

Table 4. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR

SITE 201

		GRAVITY & BOX CORES		PISTON CORE		
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	AVERAGE SED. RATE (cm/yr)
I0	225	40	0.178	40	0.178	0.178
I1	915	127	0.126	119	0.114	0.120
I2	1325	152	0.061	148	0.071	0.066
I3	1523	172	0.101	166	0.091	0.096
I4	1710			203	0.198	0.198
I5	2095			231	0.073	0.073
I6	2515			260	0.069	0.069
I7	3338			340	0.097	0.097
I8	3948			382	0.069	0.069
I9	4456			442	0.118	0.118
I10	6453			497	0.028	0.028

AVERAGE SEDIMENTATION RATE FOR SITE: 0.077 cm/yr

Table 5. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR

SITE 203/103

		203 GRAVITY & BOX CORES		203 PISTON CORE		103 PISTON CORE		AVERAGE SED.
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	RATE (cm/yr)
I1	915	50	0.055	51	0.056	58	0.063	0.058
I2	1325	75	0.061	80	0.071	94	0.088	0.073
I3	1523	80	0.025	100	0.101	112	0.091	0.072
I4	1710	90	0.053	112	0.064	130	0.096	0.071
I5	2095	155	0.169	159	0.122	200	0.182	0.158
I6	2515			195	0.086	225	0.060	0.073
I7	3338			230	0.043	270	0.055	0.049
I8	3948			270	0.066	319	0.080	0.073
I9	4456			315	0.089	375	0.110	0.100
I9.5	5350			390	0.084	498	0.138	0.111
I10	6453			440	0.045	520	0.020	0.033
I11	6772			520	0.251	604	0.263	0.257
I12	6931					685	0.509	0.509
I13	7651					711	0.036	0.036
I14	8355					787	0.108	0.108

AVERAGE SEDIMENTATION RATE FOR SITE: 0.094 cm/yr

Table 6. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR

SITE 204

		GRAVITY CORE		PISTON CORE		AVERAGE SED.
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	RATE (cm/yr)
I0	225	19	0.084			0.084
I1	915	49	0.043	50	0.055	0.049
I2	1325	80	0.076	80	0.073	0.075
I3	1523	101	0.106	96	0.081	0.094
I4	1710	122	0.112	110	0.075	0.094
I5	2095	162	0.104	159	0.127	0.116
I6	2515			178	0.045	0.045
I7	3338			218	0.049	0.049
I8	3948			237	0.031	0.031
I9	4456			285	0.094	0.094
I9.5	5350			360	0.084	0.084
I10	6453			456	0.087	0.087
I11	6772			502	0.144	0.144
I12	6931			531	0.182	0.182
I13	7651			570	0.054	0.054

AVERAGE SEDIMENTATION RATE FOR SITE: 0.075 cm/yr

Table 7. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR

SITE 214

		GRAVITY & BOX CORES		PISTON CORE		AVERAGE SED.
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	RATE (cm/yr)
I0	225	50	0.222	50	0.222	0.222
I1	915	80	0.043	70	0.029	0.036
I2	1325	105	0.061	80	0.024	0.043
I3	1523	125	0.101	105	0.126	0.114
I4	1710	155	0.160	120	0.080	0.120
I5	2095			165	0.117	0.117
I6	2515			205	0.095	0.095
I7	3338			268	0.077	0.077
I8	3948			290	0.036	0.036
I9	4456			314	0.047	0.047
I9.5	5350			361	0.053	0.053

AVERAGE SEDIMENTATION RATE FOR SITE: 0.067 cm/yr

Table 8. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR

SITE 223/122

		223 GRAVITY & BOX CORES		223 PISTON CORE		122 PISTON CORE		AVERAGE SED.
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	RATE (cm/yr)
I0	222	30	0.133	30	0.133			0.133
I1	915	125	0.138	150	0.174			0.156
I2	1325			220	0.171			0.171
I3	1523			326	0.535	307	---	0.535
I4	1710			370	0.235	355	0.257	0.246
I5	2095			440	0.260	432	0.200	0.230
I6	2515			485	0.107	500	0.162	0.135
I7	3338			658	0.210	635	0.164	0.187
I8	3948			705	0.077	690	0.090	0.084

AVERAGE SEDIMENTATION RATE FOR SITE: 0.179 cm/yr

Table 8b. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR SITE 223/122-ALTERNATE

		223 GRAVITY & BOX CORES		223 PISTON CORE		122 GRAVITY CORE		
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	AVERAGE SED. RATE (cm/yr)
I0	222	30	0.133	30	0.133	30	0.135	0.134
I1	915	125	0.138	150	0.174	48	0.026	0.113
I2	1325			220	0.171	102	0.132	0.152
I3	1523			326	0.535	139	0.187	0.361
I4	1710			370	0.235	151	0.064	0.150
I5	2095			440	0.260	183	0.083	0.172
I6	2515			485	0.107	251	0.162	0.135
I7	3338			658	0.210	386	0.164	0.187
I8	3948			705	0.077	441	0.090	0.084

AVERAGE SEDIMENTATION RATE FOR SITE: 0.165 cm/yr

Table 9. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR

SITE 222

		GRAVITY & BOX CORES		PISTON CORE		AVERAGE SED.
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	RATE (cm/yr)
I0	222	19	0.084			0.084
I1	915	78	0.086	62	0.068	0.077
I2	1325			228	0.040	0.040
I3	1523			280	0.263	0.263
I4	1710			330	0.267	0.267
I5	2095			408	0.203	0.203
I6	2515			445	0.088	0.088
I7	3338			685	0.292	0.292
I8	3948			727	0.069	0.069

AVERAGE SEDIMENTATION RATE FOR SITE: 0.184 cm/yr

Table 10. DEPTH OF INCLINATION FEATURES AND SEDIMENTATION RATES FOR

SITE 217

		GRAVITY CORE		PISTON CORE		AVERAGE SED.
FEATURE	AGE (years BP)	CORE DEPTH (cm)	SED. RATE (cm/yr)	CORE DEPTH (cm)	SED. RATE (cm/yr)	RATE (cm/yr)
I1	915	18	0.020	18	0.020	0.020
I2	1325	23	0.012	25	0.017	0.015
I3	1523	28	0.025	31	0.03	0.028
I4	1710	42	0.075	48	0.091	0.083
I5	2095	63	0.055	63	0.039	0.047
I6	2515	82	0.045	83	0.048	0.047
I7	3338			172	0.108	0.108

AVERAGE SEDIMENTATION RATE FOR SITE: 0.043 cm/yr

Table 11:
Comparison of Radiocarbon and SV Dates from Lake Winnipeg Cores

LW Core	Adjusted Interval (cm)	Fossil Type	AMS 14C Date (yrs)	Secular Variation 14C Date (yrs)	Δ years
201	439-444	spruce needles	4800 ± 70	4464	-336
204	382-393	ostracodes	6700 ± 80	5558	-1142
204	513-518	spruce needle	6750 ± 70	6956	+ 206
214	288-293	wood fragment	3630 ± 50	3962	+ 332
122	665-673	Scirpus seed	4040 ± 70	3545	-495
223	527-529	Scirpus seed	3280 ± 60	2917	-363
223	681-686	Scirpus seed	4000 ± 60	3459	-541
217	127-132	Scirpus seed	3340 ± 50	2946	-394

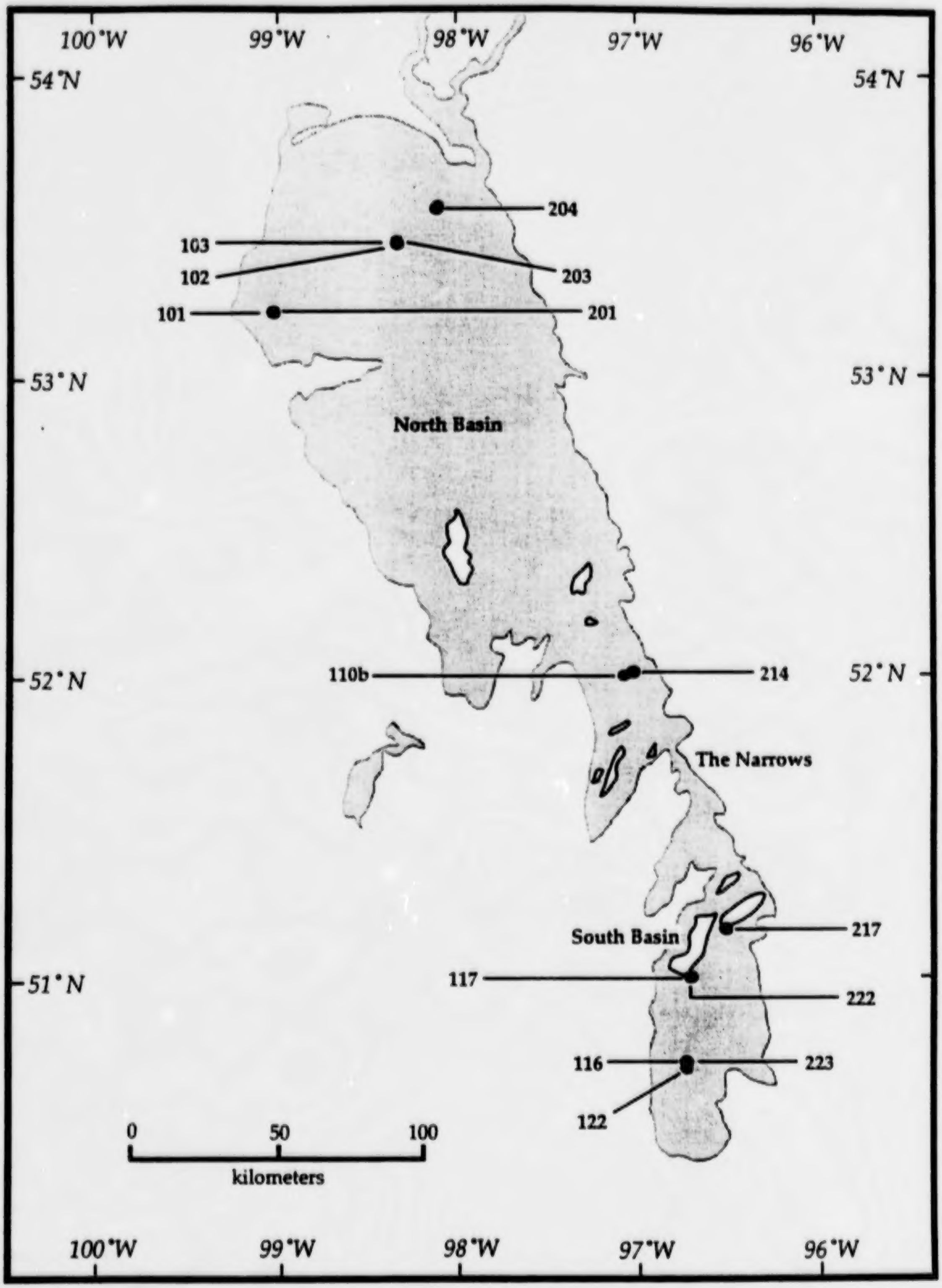
100°W
99°W
98°W
97°W
96°W
54°N
54°N
204
103
102
203
101
201
53°N
53°N
North Basin
110b
214
52°N
52°N
The Narrows
South Basin
217
117
222
51°N
51°N
116
223
122
0
50
100
kilometers
100°W
99°W
98°W
97°W
96°W

Figure 1

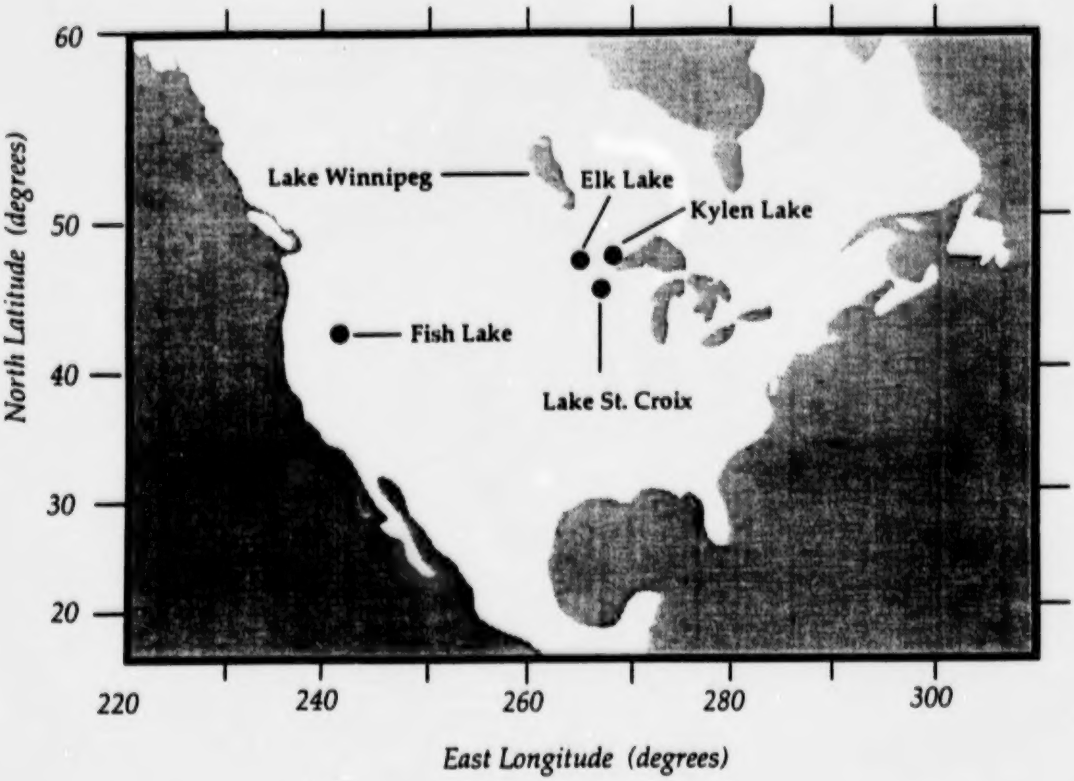

60
50
40
30
20
220
240
260
280
300
North Latitude (degrees)
East Longitude (degrees)
Lake Winnipeg
Elk Lake
Kylen Lake
Fish Lake
Lake St. Croix

Figure 2

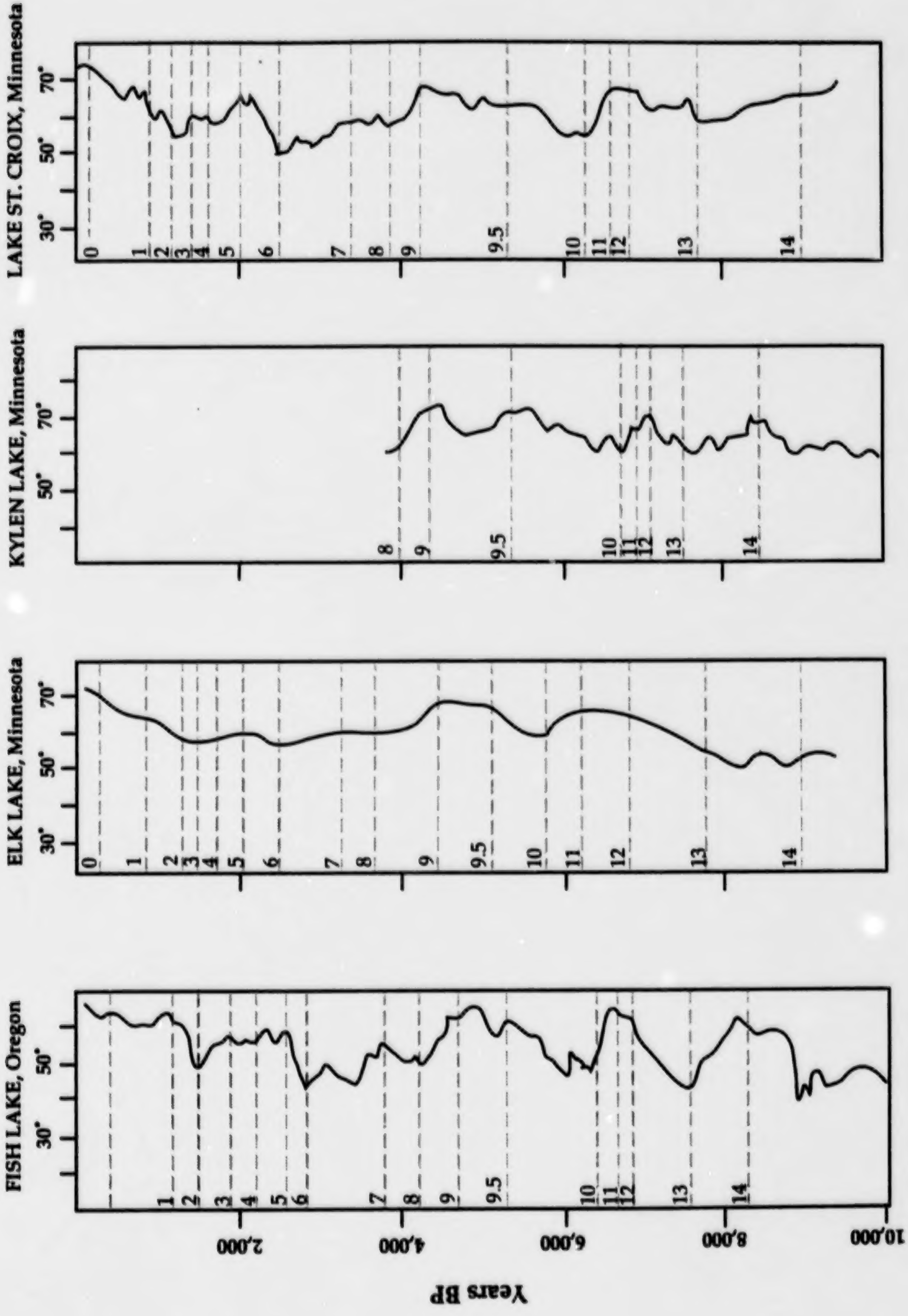
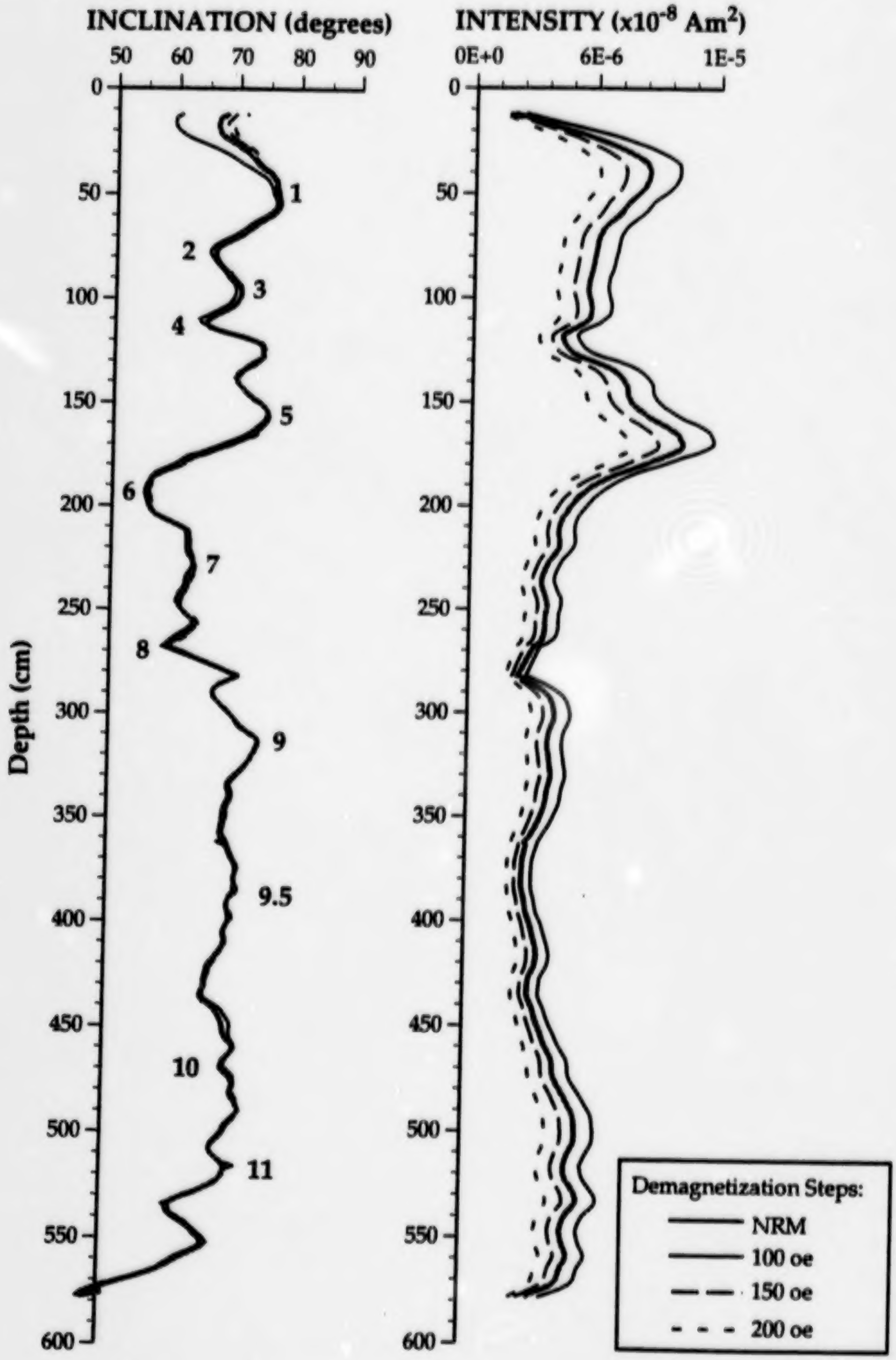

LAKE ST. CROIX, Minnesota
KYLEN LAKE, Minnesota
ELK LAKE, Minnesota
FISH LAKE, Oregon
30°
50°
70°
0
1
2
3
4
5
6
7
8
9
9.5
10
11
12
13
14
2,000
4,000
6,000
8,000
10,000
Years BP

Figure 3



96900-PC 203

Figure 4

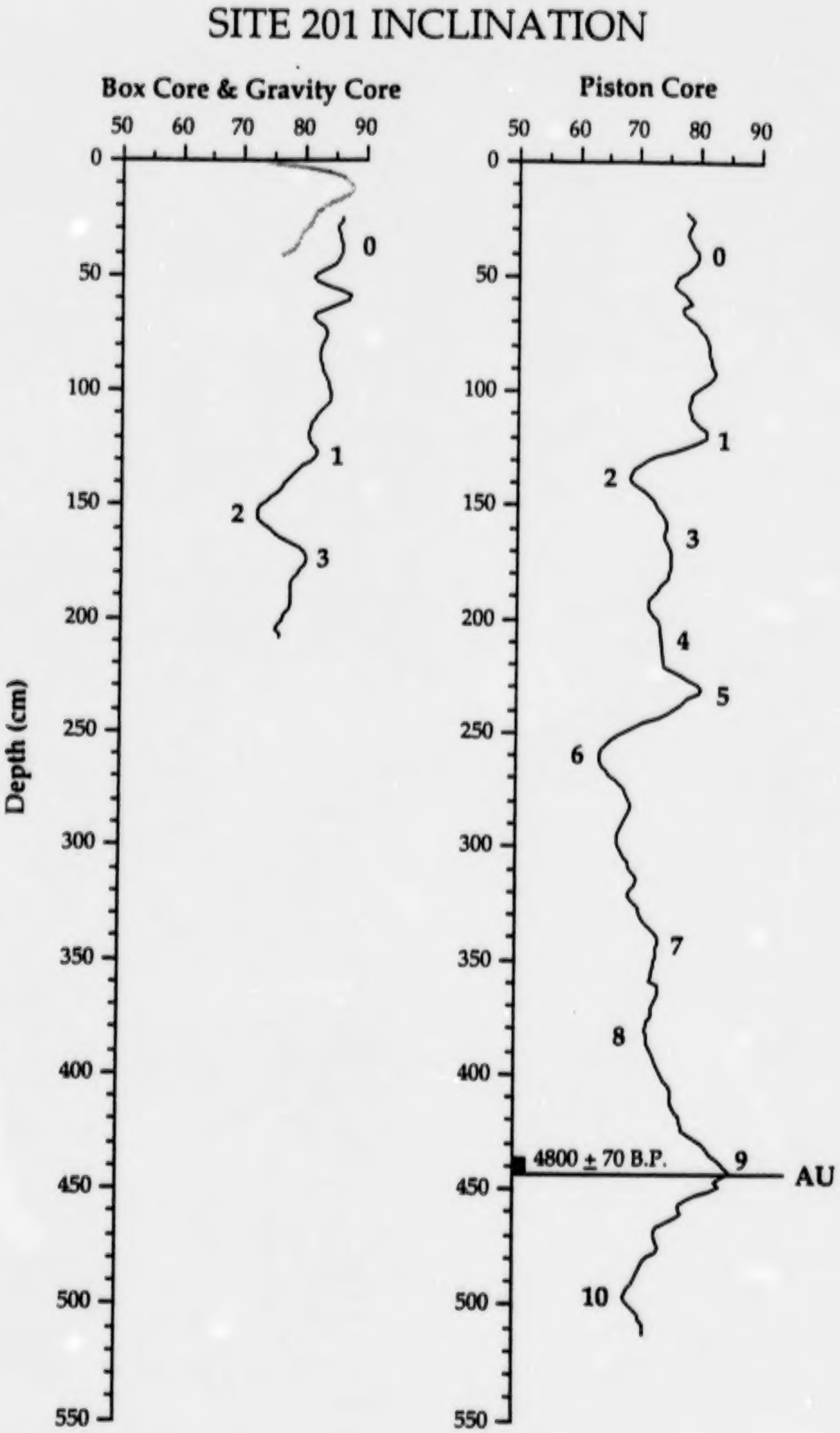
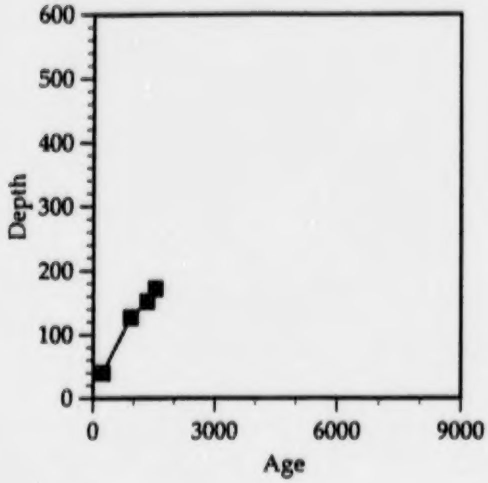
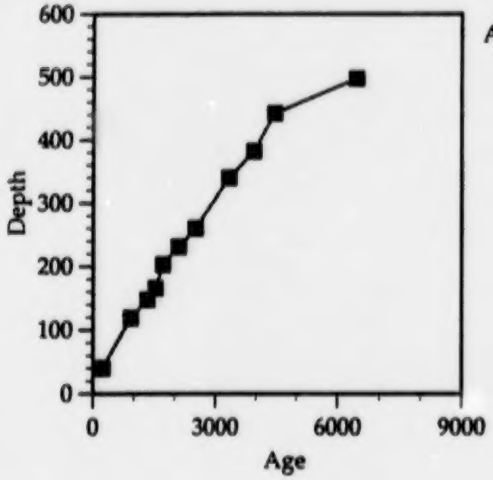

SITE 201 INCLINATION
Box Core & Gravity Core
Piston Core
50
60
70
80
90
Depth (cm)
0
50
100
150
200
250
300
350
400
450
500
550
0
1
2
3
4
5
6
7
8
9
10
4800 ± 70 B.P.
AU

Figure 5

201: Box Core & Gravity Core





AU = 443 cm, 4464 years

Figure 6

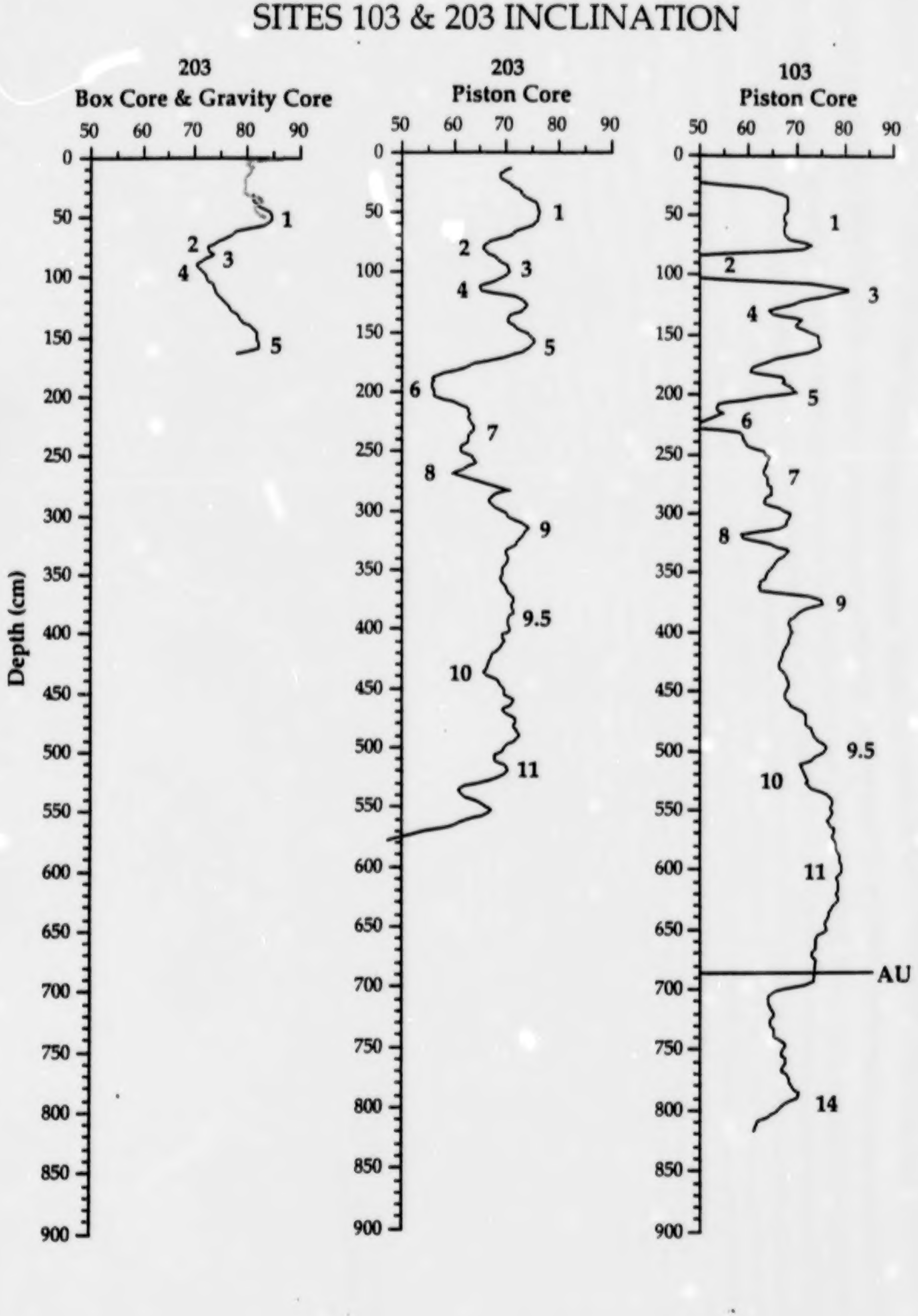
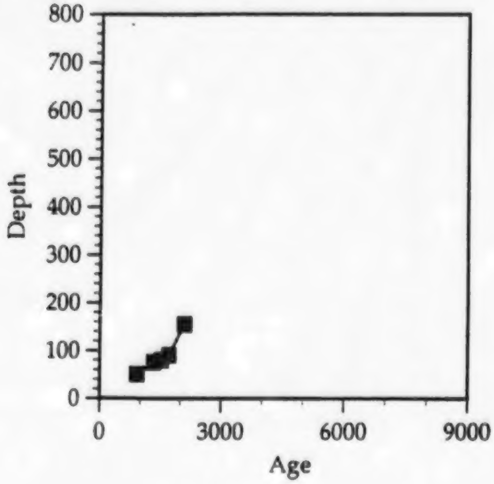
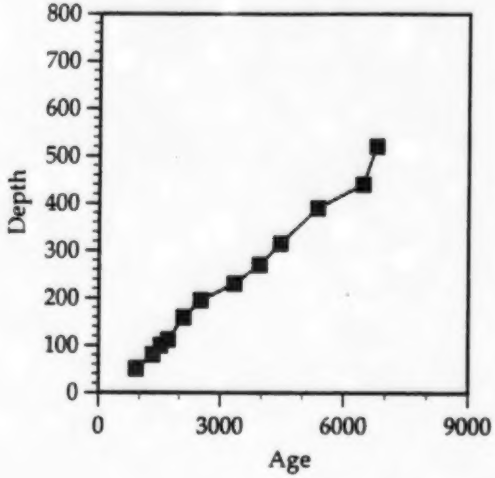

SITES 103 & 203 INCLINATION
203
Box Core & Gravity Core
203
Piston Core
103
Piston Core
50
60
70
80
90
Depth (cm)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
1
2
3
4
5
6
7
8
9
9.5
10
11
14
AU

Figure 7

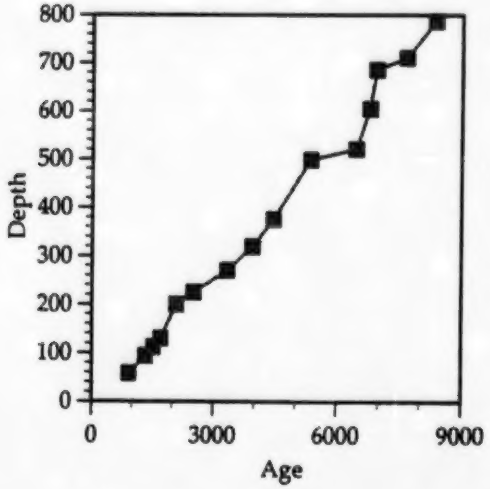
203: Box Core & Gravity Core



203: Piston Core

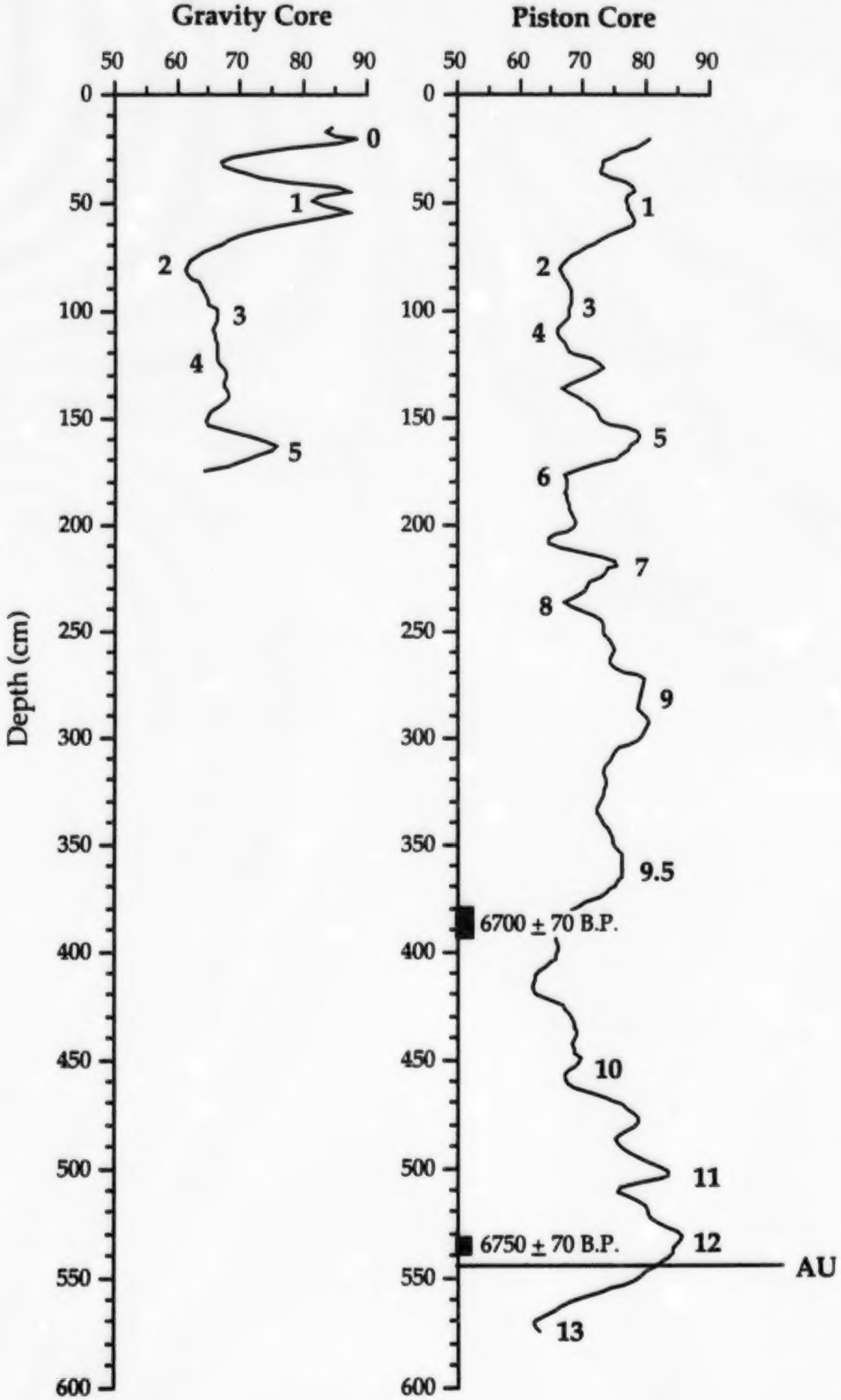


103: Piston Core



AU = 686 cm, 6959 years

Figure 8

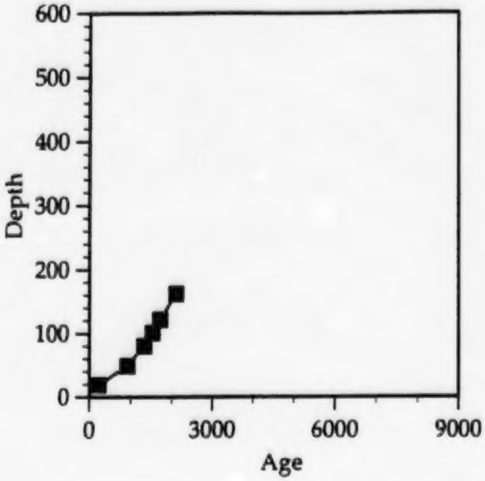


SITE 204 INCLINATION

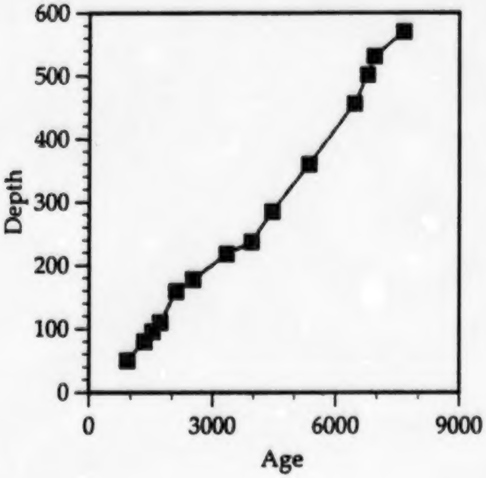
Gravity Core

Piston Core

Figure 9



204: Gravity Core



204: Piston Core

Figure10

SITE 214 INCLINATION

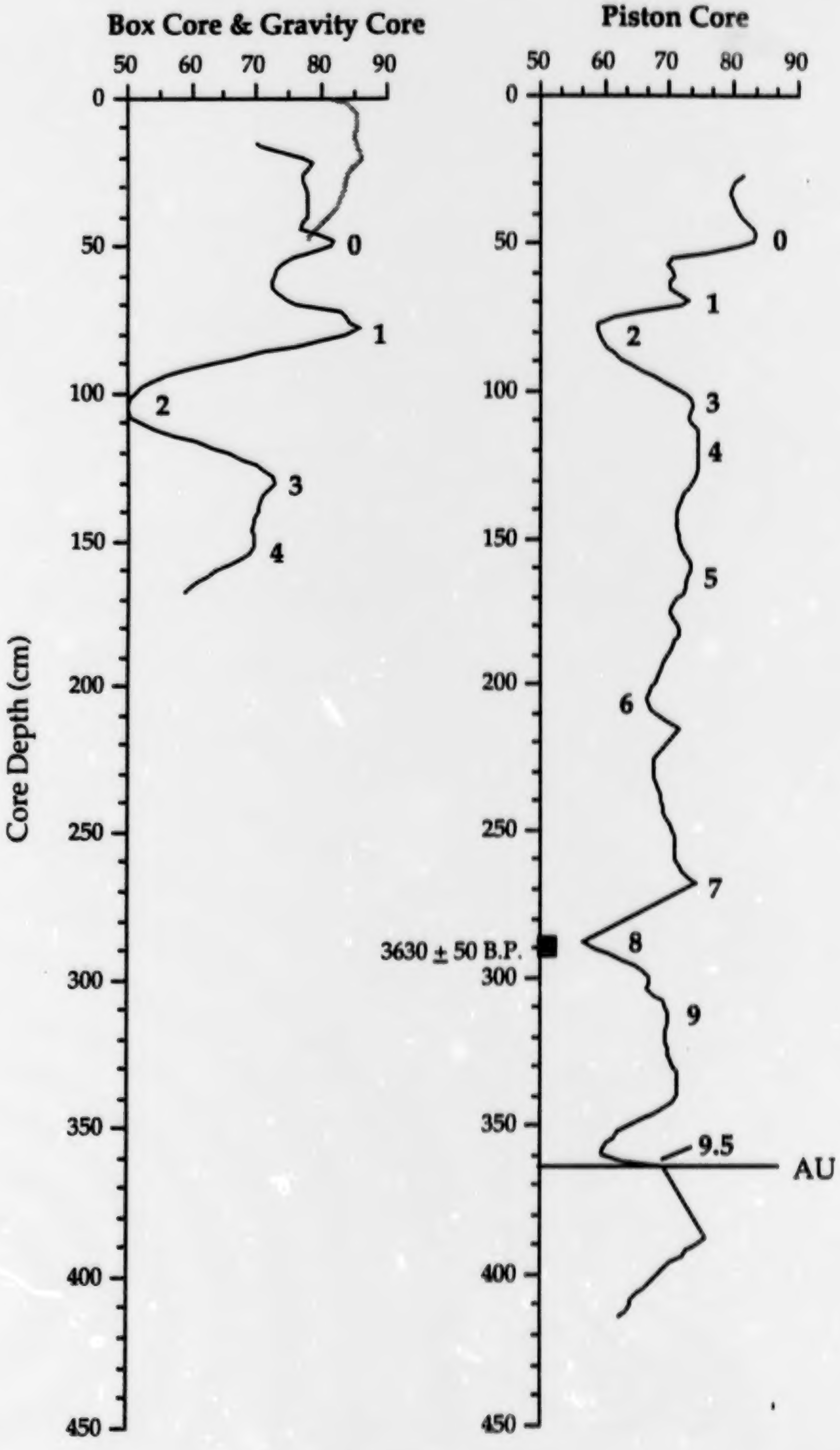
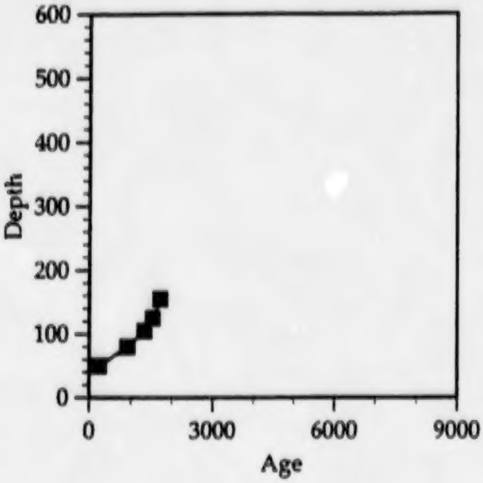
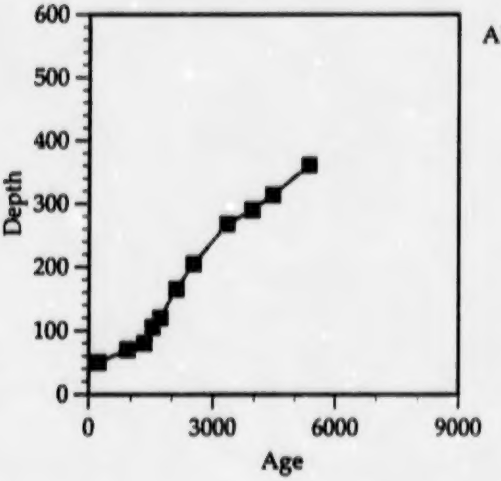


Figure 11



214: Box Core & Gravity Core



214: Piston Core

AU = 365 cm, 5425 years

Figure 12

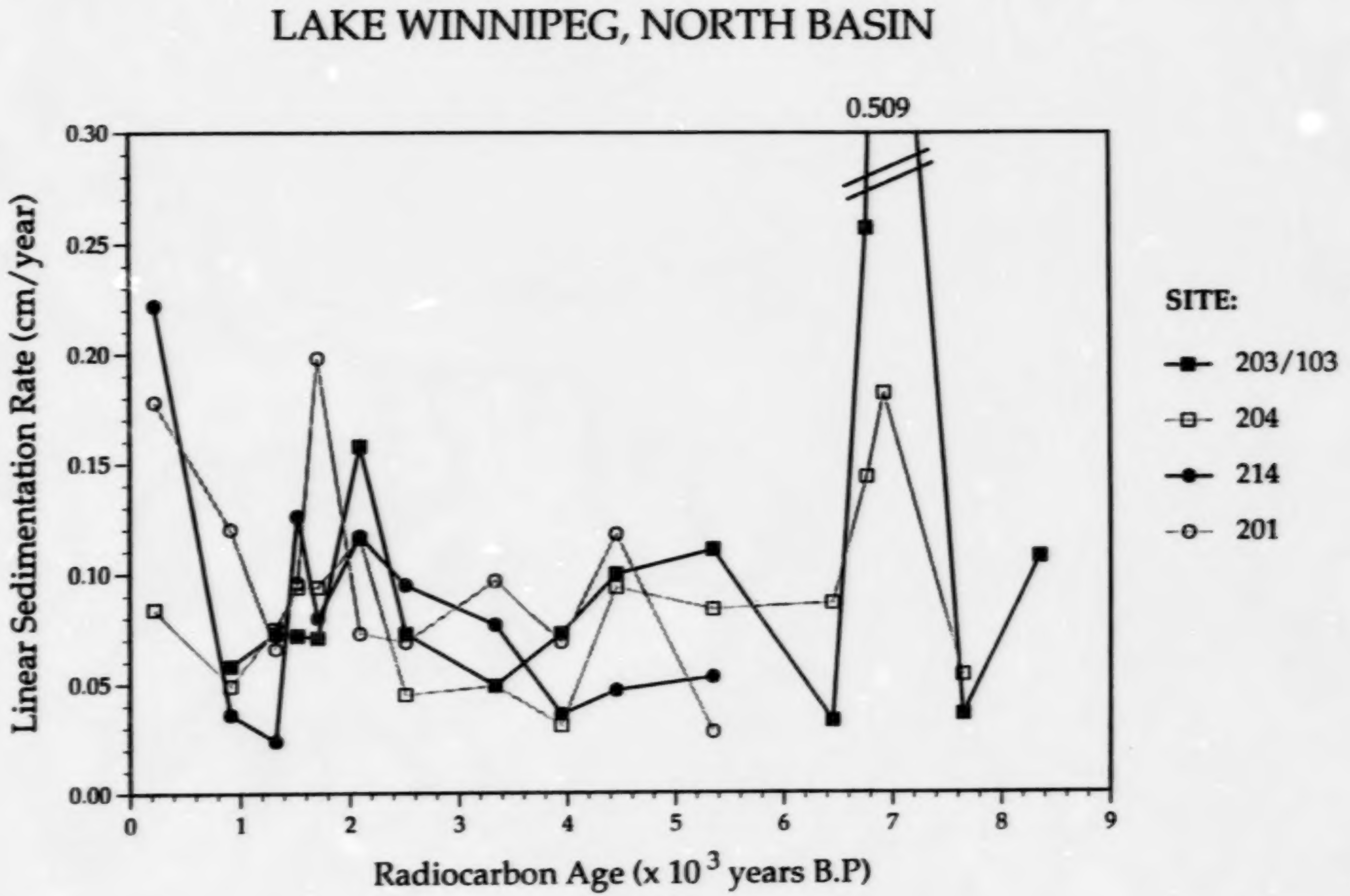

LAKE WINNIPEG, NORTH BASIN
0.509
Linear Sedimentation Rate (cm/year)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
8
9
Radiocarbon Age (x 10 3 years B.P)
SITE:
203/103
204
214
201

Figure 13

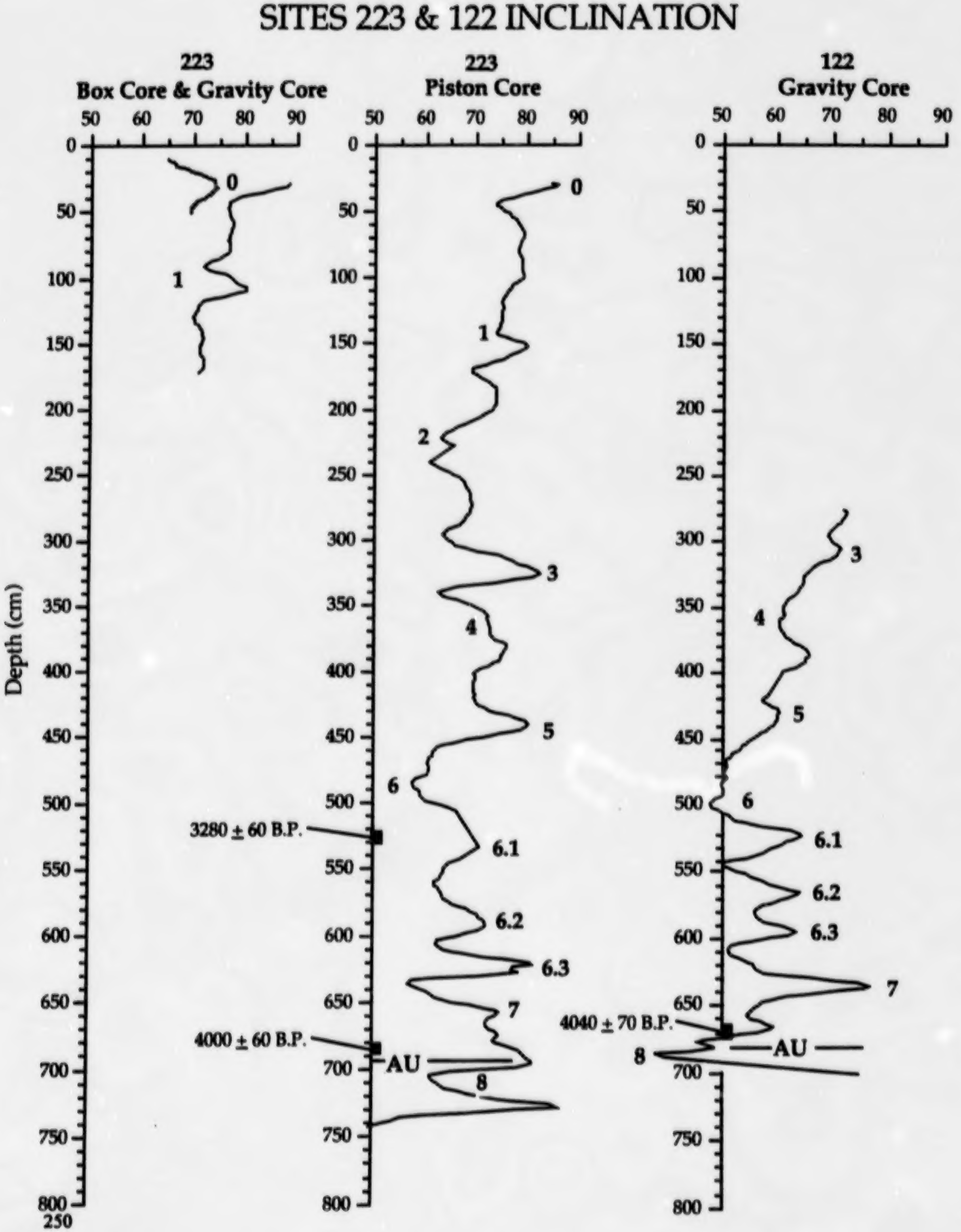
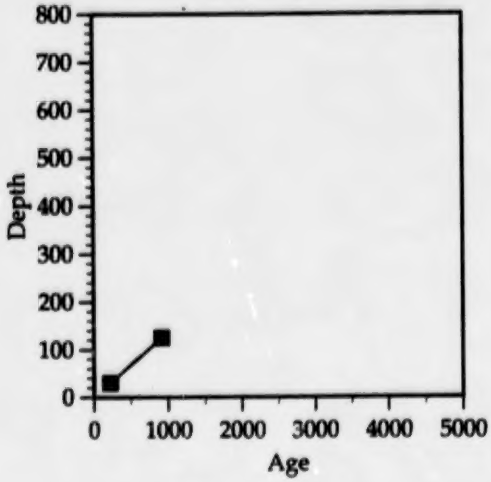
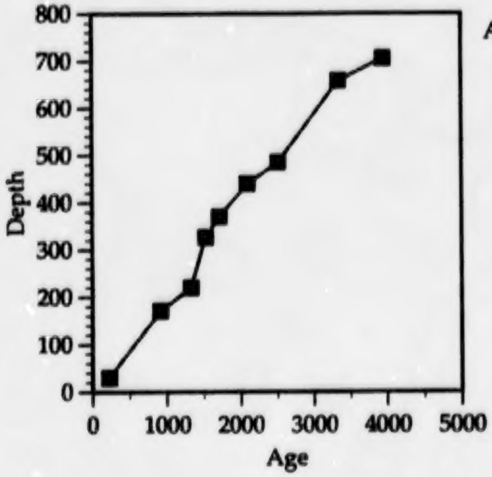

SITES 223 & 122 INCLINATION
223
Box Core & Gravity Core
223
Piston Core
122
Gravity Core
50
60
70
80
90
Depth (cm)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
0
1
2
3
4
5
6
6.1
6.2
6.3
7
8
AU
3280 ± 60 B.P.
4000 ± 60 B.P.
4040 ± 70 B.P.

Figure 14

223: Gravity Core & Box Core

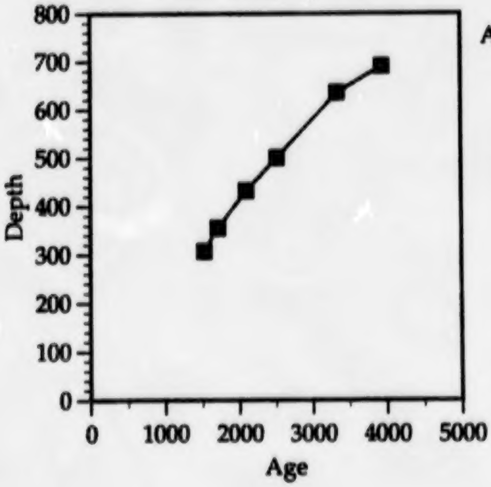


223: Piston Core



AU = 697.5 cm, 3851 years

122: Gravity Core



AU = 680 cm, 3837 years

Figure 15

SITE 222 INCLINATION

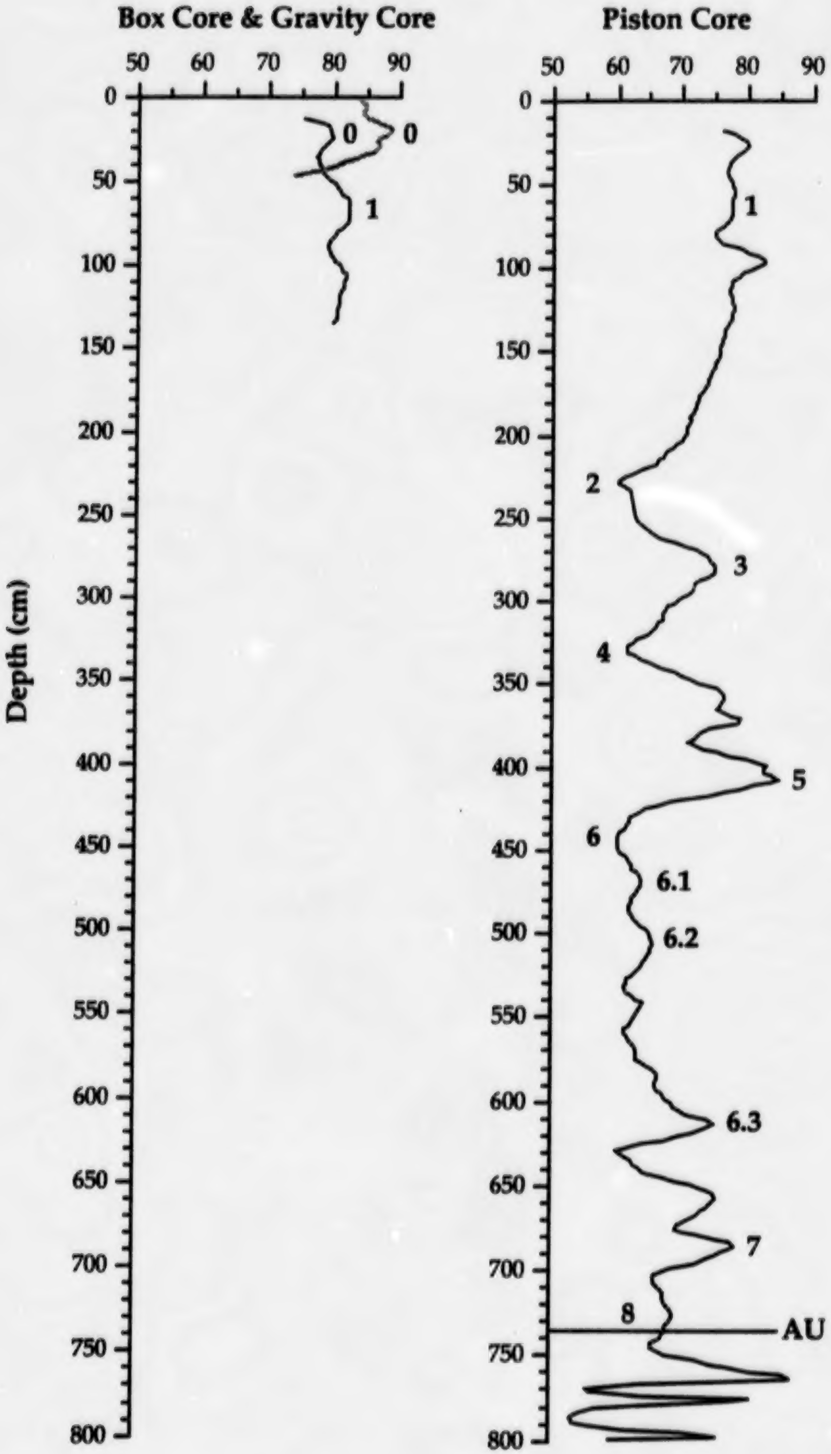
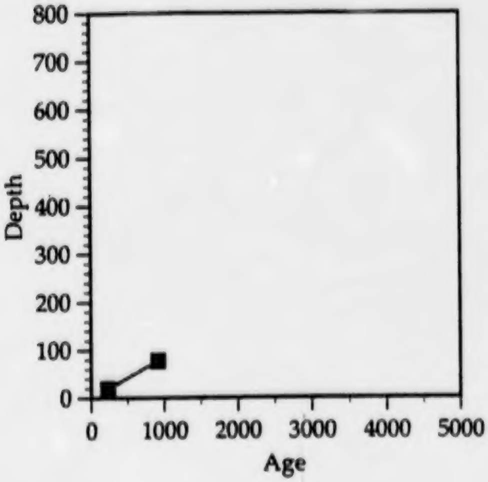
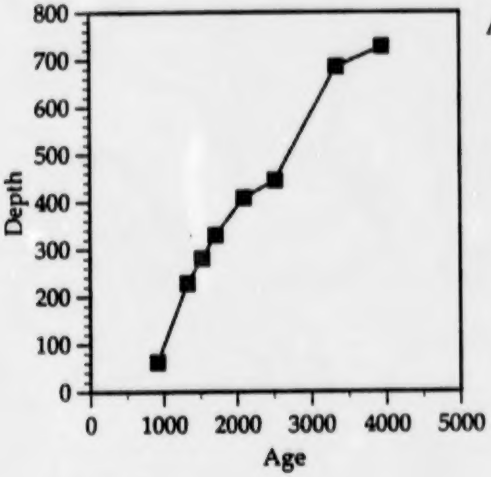


Figure 16

222: Gravity Core



222: Piston Core



AU = 735 cm, 4064 years

Figure 17

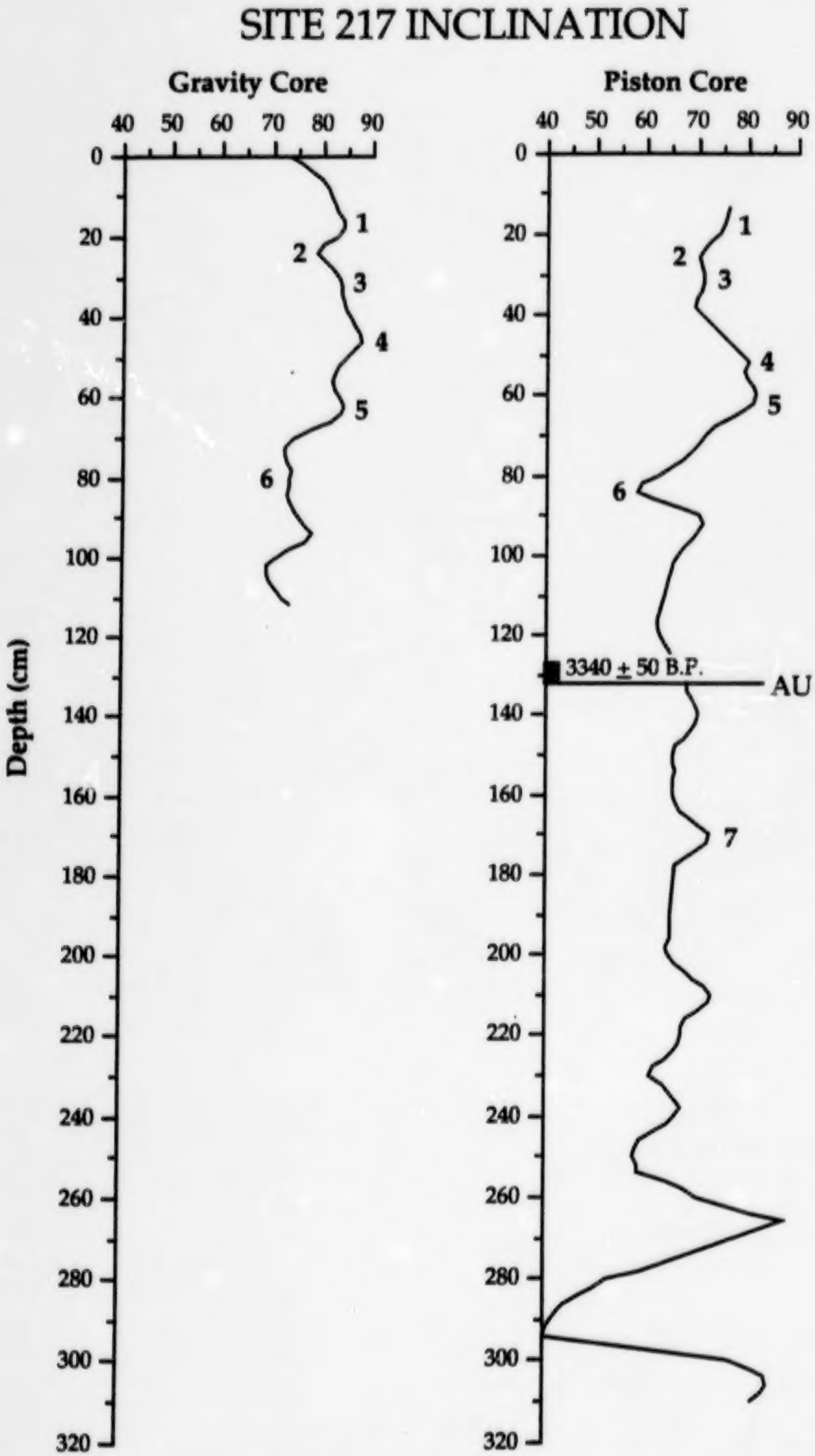
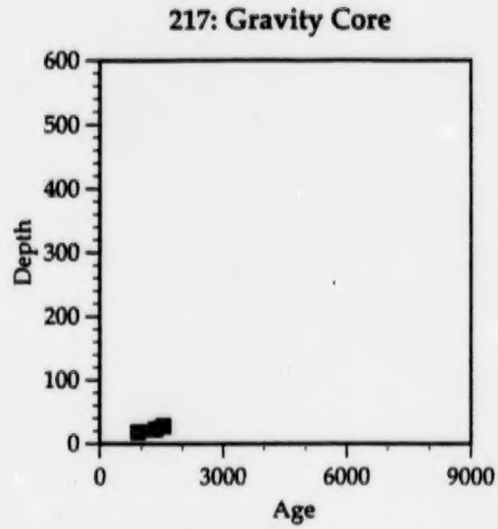
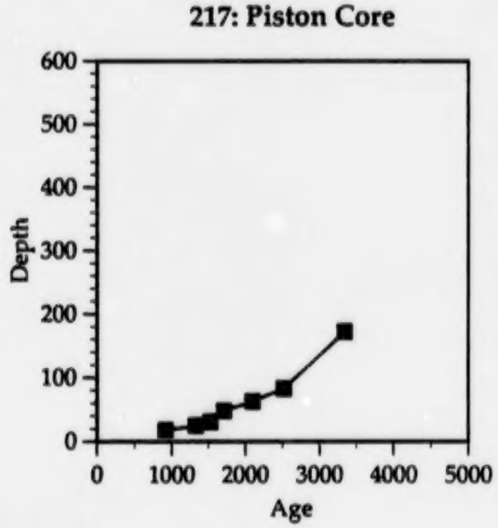

SITE 217 INCLINATION
Gravity Core
Piston Core
40 50 60 70 80 90
40 50 60 70 80 90
Depth (cm)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
1
2
3
4
5
6
1
2
3
4
5
6
3340 ± 50 B.P.
AU
7

Figure 18



217: Gravity Core



217: Piston Core

U= 133 cm, 2978 years

Figure 19

LAKE WINNIPEG, SOUTH BASIN

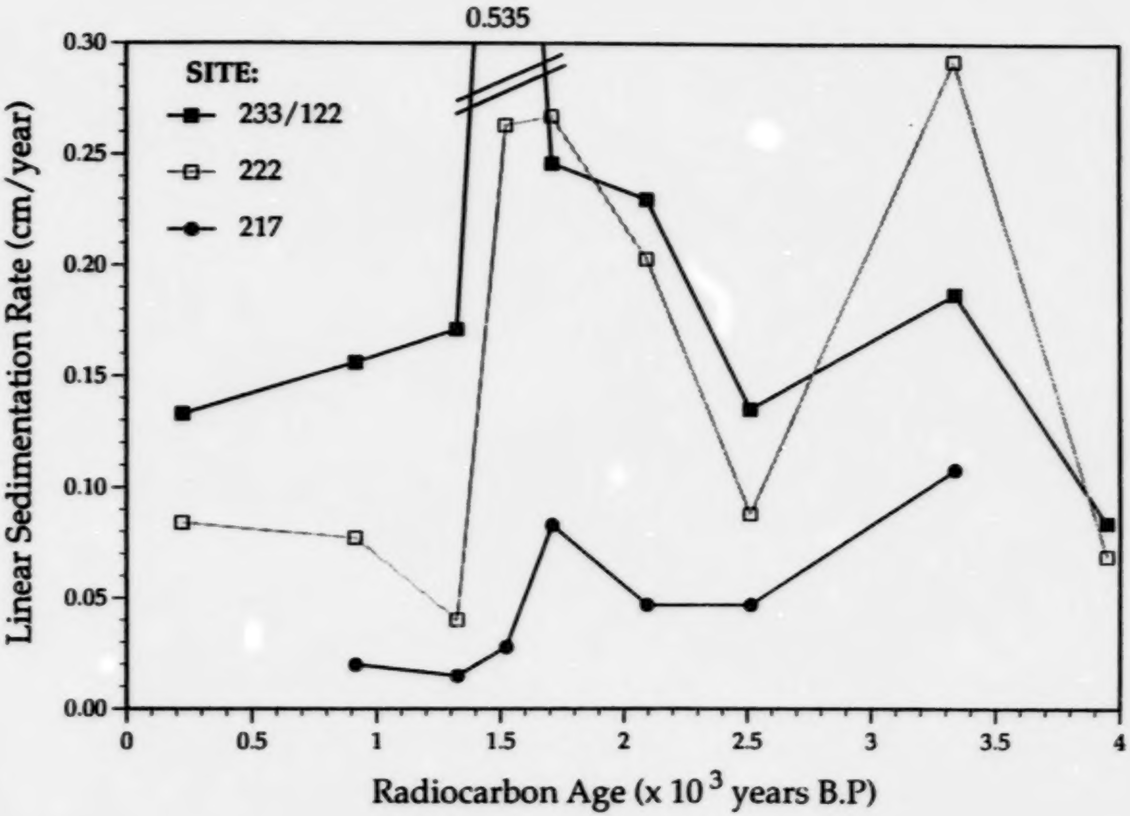


Figure 20

7.2 Studies of dated sediment cores from Lake Winnipeg, 1994

W. L. Lockhart[1], P. Wilkinson[1], B. N. Billeck[1], G. A. Stern[1], R. A. Danell[1], J. DeLaronde[1] and D.C.G. Muir[2]

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2. Environment Canada, 867 Lakeshore Road, Burlington, Ontario L7R 4A6

INTRODUCTION

Box cores, piston cores and dredge samples were collected in August, 1994, during a cruise of the CCGS *Namao*. Initial results from the dredges and from two piston cores were tabulated by Lockhart (1996). This report describes initial results from three of the box cores. Core sites were selected based on sediment characteristics revealed by sub-bottom profiling (Todd and Lewis, 1996). This report describes results from three cores, namely core 2 from the North Basin (53° 28.10' N, 98° 20.20' W), core 7 from the South Basin (50° 39.86' N, 96° 47.98' W), and core 9 from the outer part of Traverse Bay (50° 45.32' N, 96° 29.15' W). Note that these three locations correspond to sites 102, 116 and 118, respectively, following the site designations given by Todd (1996).

Mercury pollution has been a serious problem for fisheries of Lake Winnipeg and its watershed. In the 1970s fisheries were closed in parts of two major tributaries, the English-Wabigoon system draining into Traverse Bay in the South Basin and the Saskatchewan system draining through Cedar Lake to the North Basin. The Lake Winnipeg fishery was closed in 1970 because mercury levels in fish exceeded levels established to protect human health. Fish from the South Basin were more highly contaminated than fish from the North Basin and several species were affected (Province of Manitoba, 1971). Surface sediment from dredge samples taken in the South Basin contained higher concentrations of mercury than those taken in the North Basin (Lockhart, 1996). Preliminary study of mercury levels in mayflies suggests that they contained higher levels of mercury in the South Basin than in the North Basin (Arnold et al., 1997).

Based on the results from cores 2 and 7, Lockhart et al. (1998) calculated the flux of mercury to the South Basin to be 114 $\mu g^{-2} y^{-1}$ and that to the North Basin 26 $\mu g^{-2} y^{-1}$. These fluxes were partitioned into what the authors described as natural and anthropogenic components based on the shapes of the down-core profiles, taking the enrichment in upper core slices as the anthropogenic contribution assuming the enrichment in upper layers was due to increased inputs. The anthropogenic components were estimated to be 61 and 13 $\mu g^{-2} y^{-1}$ for the South and North Basins respectively. Lakes at comparable latitude in northwestern Ontario and north-central USA (Swain et al. 1992; Lockhart et al. 1998) had anthropogenic components of only about 9 $\mu g^{-2} y^{-1}$.

CORE COLLECTION

Core samples were taken using an oceanographic box corer to obtain a large block of sediment; short cores were then taken from the box of sediment after it was retrieved onto the deck of the ship. Plastic core tubes (10 cm inside diameter) were inserted into the sediment using gentle vacuum to minimize sediment compaction during insertion of the tube. Cores were sectioned, usually into 1-cm sections, by placing the full tube on a plunger and extruding the sediment through the top. Extruded slices were bagged individually in Whirlpak® plastic bags and stored in a refrigerator until the ship reached port when they were transferred to the Freshwater Institute and freeze dried prior to analysis.

CORE DATING

Lead-210 and radium-226 were measured as described in Lockhart et al. (1998) by leaching the sediment with hydrochloric acid at 80°C. Polonium-210, the daughter of lead-210, was autoplated onto a silver disc from 1.5N HCl and the disc was counted with an alpha spectrometer (Flynn, 1968); lead-210 was determined from the activity of polonium-210. The remaining acid solution was analyzed for Ra-226 by the radon de-emanation method of Mathieu (1977). Cesium-137 was counted on freeze-dried sediment using a gamma spectrometer. Mean ages of slices were estimated from the regression of unsupported lead-210 against accumulated dry weight. When combined with the Cs-137 profiles, the Pb-210-derived dates are considered credible if they placed the peak activity for Cs-137 during the 1960s. The measured deposition rate of Pb-210 was compared with that expected for the area as calculated from a soil profile taken at the Experimental Lakes Area. That profile indicated a flux of

175 Bq m^{-2}y^{-1} (Lockhart et al, 1998). We compared the measured flux of Pb-210 with the expected flux to estimate the amount of sediment focusing at each core site. If the Pb-210 flux from a core was higher than 175 Bq m^{-2}y^{-1} then the difference was taken to represent focusing of excess sediment to the core site.

MERCURY IN SEDIMENT

Mercury in sediment was analyzed as reported previously (Lockhart et al., 1993, 1995, 1998) by boiling a small amount of sediment (0.1-0.5 g) with 8 ml of aqua regia and bringing the volume to 50 ml with distilled water. The supernatant was reduced with stannous sulfate and hydroxylamine and analyzed for mercury by cold vapour atomic absorption spectrophotometry (Hendzel and Jamieson, 1976).

PAHs IN SEDIMENT

Freeze dried sediment slices were fortified with a solution containing 100 ng of each of seven deuterated PAHs and then soxhlet extracted in glass thimbles using dichloromethane (Giger and Schaffner, 1978; McVeety and Hites, 1988). Extracts were cleaned to remove sulfur using activated copper powder with susequent fractionation on silica/alimina columns (Boehm, 1983). Compounds were separated with a bonded phase, 30 m x 0.25 mm, J & W, DB-5 fused silica capillary column. PAHs were identified and expressed quantitatively with a Hewlett Packard MSD operated in the single ion monitoring mode using the ratio of analyte to the nearest deuterated compound for quantitation.

The following PAHs were measured: Naphthalene, 1-Methylnaphthalene, 2-Methylnaphthalene, 2,6-Dimethylnaphthalene, 1,4-Dimethylnaphthalene, 1,2-Dimethylnaphthalene, 2,3,6-Trimethylnaphthalene, 2,3,5-Trimethylnaphthalene, Sum of C3 Naphthalene, Sum of C4 Naphthalene, Dibenzofuran, Acenaphthylene, Acenaphthene, Fluorene, 1-Methylfluorene, Sum of C1 Fluorene, Sum of C2 Fluorene, Sum of C3 Fluorene, Dibenzothiophene, Sum of C1 Dibenzothiophene, Sum of C3 Dibenzothiophene, Phenanthrene, Anthracene, 1-Methylphenanthrene, 9-Methylanthracene, 2-Methylphenanthrene, 2-Methylanthracene, Sum of C1 Phenanthrene/Anthracene, 3,6-Dimethylphenanthrene, 9,10-Dimethylphenanthrene, Sum of C2 Phenanthrene/Anthracene, Sum of C3 Phenanthrene/Anthracene, Sum of C4 Phenanthrene/Anthracene, Fluoranthene, Pyrene, Sum of C1 Pyrene, Sum of C2 Pyrene, Sum of C3 Pyrene, Retene, Benzo(a)anthracene , Triphenylene, Chrysene, Sum of C1 Chrysene, Sum of C2 Chrysene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Benzo(e)Pyrene, Benzo(a)pyrene, Perylene, Dibenzo(a,h)anthracene, Indeno(1,2,3-c,d)pyrene, Benzo(g,h,i)perylene.

TOXAPHENE IN SEDIMENT

Freeze dried sediment was analyzed for toxaphene by high-resolution electron capture negative ion mass spectrometry (Stern et al., 1996). Pairs of slices were pooled partly to reduce analytical costs and partly to obtain a greater weight of material to extract.

RESULTS AND DISCUSSION

Lead-210 and cesium-137 in sediments

Down-core profiles of Pb-210 and Cs-137 for the three cores are shown in Figure 1 with dates derived from the Pb-210 curves. In all three instances the Pb-210 dates placed peak Cs-137 activity in the 1960s and so the Pb-210 dates are interpreted as credible. There was relatively little evidence of focusing at any of the sites since Pb-210 fluxes were 136 Bq m^{-2}y^{-1} at the Traverse Bay (core 9), 195 Bq m^{-2}y^{-1} (core 7) and 216 Bq m^{-2}y^{-1} (core 2) in the North Basin. The flux of Pb-210 to soil at the Experimental Lakes Area of 175 Bq m^{-2}y^{-1} (Lockhart et al., 1998) is taken to be the flux expected in the absence of any import or export of sediments from the core site. On this basis, cores 2 and 7 received slightly more material than expected and core 9 received slightly less.

The cesium profiles suggested a some vertical mixing by this isotope because low, but measurable, activities were detected in slices dating to the 1930s (cores 7 and 9). The processes responsible for this mixing is unknown but may have included particle mixing by benthic organisms or diffusion through pore water or other mechanisms. Probably most cores are mixed to some degree and this may or may not be sufficient to obscure historical records. In these instances mixing did not obscure the cesium-137 peak which coincided with peak bomb fallout in the 1960s. There was a surprisingly slow return to basal activities following peak inputs in the 1960s. Indeed, there were even slight increases in some slices over deeper ones during the 1970s and 1980s which suggests a source of cesium in addition to bomb fallout. This is consistent with information on cesium-137 from the Winnipeg River upstream and downstream from the Whiteshell Nuclear Research Establishment (Winnipeg River Task Force, 1995). Those data indicate higher levels downstream from the research station for about a decade between the early1970s to the early1980s. It seems likely that some of the cesium lost from the research facility reached Lake Winnipeg and became widely dispersed there. More evidence for this dispersal was the detection of small amounts of cesium-134 in the top slices of a core taken from the South Basin in 1980 (Brunskill and Wilkinson, unpublished data).

Mercury, cadmium and lead in cores

Profiles for mercury, cadmium and lead in the three cores are shown in Figure 2. Mercury increases in the upper slices in all three cores implying recent inputs greater than those when the deeper slices were deposited. Taking the slice dates indicated from the lead-210 profiles, the increases in core 2 from the North Basin occurred mostly during the 1950s with little change since 1960. Core 7 taken off Gimli showed increases since early in the 1900s, possibly extending back to the late 1800s. Core 9 from outer Traverse Bay had most of the increase in mercury during the period from the 1920s to about 1950 with very slow increase earlier in the century and a subsequent decline in inputs after 1950. The profiles from these cores are very similar to those reported by Brunskill and Graham (1979). Also, surface sediment concentrations of mercury in their South Basin cores ranged from about 94 to 150 ng g^{-1}, in close agreement with our value of 129 ng g^{-1} for core 7 in 1994. Interestingly, these concentrations in surface sediments in the lake are considerably higher than those reported in streams in the upper parts of the watershed. Brigham et al. (1998) analyzed many metals in stream sediments in the U.S. portion of the Red River watershed and found values for mercury mostly in the range of about 20-80 ng g^{-1}. Samples of suspended matter collected from the Red River upstream and downstream from Winnipeg during the flood of 1997 had mercury contents of 59 and 176 ng g^{-1} respectively (Lockhart, unpublished data). Similarly, lead in suspended matter was about twice as high downstream (31.5 $\mu g\ g^{-1}$) as upstream (16.5 $\mu g\ g^{-1}$). These data suggest sources of mercury, in addition to background geology and atmospheric fallout at locations, somewhere north of the U.S. border, probably the city of Winnipeg.

Grain size distribution was determined for one of these cores by the University of Manitoba, Geological Sciences Department (Dr. W.M. Last). Slices of core 2 had clay-sized material ranging from 16 to 69 per cent while clay minerals were more consistent with a range of 54 to 77 per cent. The proportion of clay-sized material tended to increase with depth except for the top two slices so that mercury and clay-sized materials were negatively correlated. Clay minerals had no clear pattern down the depth of the core and were not correlated with mercury.

Organic carbon levels (taken as the difference between total C and carbonate C) were measured in every fifth slice of core 2 and in all the slices of core 7. Levels increased from 11 mg g^{-1} at the bottom of core 2 to 66 mg g^{-1} at the top with most of the increase in the top 5 slices. The organic carbon in core 7 changed much less, from 12 mg g^{-1} at the bottom to 20 mg g^{-1} at the top. In both these cores there were statistical associations between organic carbon and mercury, with an r^2 value of 0.48 in core 2 and 0.88 in core 7. The mercury profiles shown in Figure 2 are repeated in Figure 3 with the addition of the organic carbon profiles. It seems likely that the processes responsible for the increases in organic carbon are different from those responsible for the increases in mercury in core 2 because the major increases in the two components are several slices out of phase. In core 7 the increase in organic carbon was quite small and consistent over the core whereas the change in mercury was more rapid in the middle part of the core than in the top or bottom. For comparison, Figure 3 also includes a core from Lake 375 from the Experimental Lakes Area on Northwestern Ontario. In that instance, the organic carbon levels were much higher and the statistical correlation between mercury and organic carbon was negative.

There were no clear trends with depth in cadmium concentrations (Figure 2). The dredge samples had higher cadmium concentrations in samples from the South Basin than from the North Basin but the cores provided no evidence of whether that difference is natural or related to human activities.

Lead profiles are similar to mercury profiles although changes with depth were less striking than with mercury. All three cores suggested some evidence of increased loadings with lead over earlier loadings indicated by the deeper slices. Studies in Europe have shown that lake sediments can preserve histories of loadings with lead for over 2000 years (Renberg et al., 1994) and so the levels for lead at the deepest slices of these short cores probably do not represent true geological background concentrations. Cores 2 and 7 suggest a decline in lead inputs to slices deposited since the late 1970s and that is consistent with other observations of Boutron et al. (1991) and with the conversion to unleaded gasoline in North America (Rosman et al., 1994).

Polycyclic aromatic hydrocarbons in core 7

Core 7 has been analyzed for several polycyclic aromatic hydrocarbons and the results for a few of these compounds are shown in Figure 4. The profile for the sum of PAHs shows increasing concentrations starting about slice 30 which was deposited before 1900. That was followed by increasing inputs of PAHs until a broad plateau of little change was reached extending from the 1920s and until the 1950s and then a gradual decline until the present. The pattern of peak concentrations below the surface has been reported in several other North American lakes (e.g. Gschwend and Hites, 1981). PAHs are byproducts of the incomplete combustion of carbon-based fuels; burning of coal and wood are both sources of PAHs. The sub-surface pattern of the down-core distribution of PAHs has been interpreted as a response to the widespread conversion of home heating in North America from coal to other fuels. The down-core distributions of two PAHs usually considered to be principally from combustion, fluoranthene and pyrene, are similar to that for the sum of all the PAHs from naphthalene to benzo(g,h,i)perylene (Fig. 4). This also suggests a decline in these combustion-related byproducts since the mid-1900s.

Combustion, however, appears unlikely to be the only source of PAHs to the South Basin. Figure 4 also shows the distributions of phenanthrene and dibenzothiophene and the C2 alkylated forms of them. An excess of alkylated forms over parent forms is sometimes indicative of a petroleum source as is the ratio of alkylated dibenzothiophenes to alkylated phenanthrenes (Steinhauer and Boehm, 1992; Yunker et al., 1993). The ratios of these compounds in the core suggest that the South Basin has received inputs of unburned petroleum in addition to fallout of combustion byproducts.

Toxaphene in core 7

Figure 5 shows the concentration profile of total toxaphene in a core 7 from the South Basin. The curve represents the atmospheric input (source) function for toxaphene which has been shown to reflect the sales and production history of toxaphene, with maximum usage occurring on the early to mid 1970s (Rapaport, 1988).

Toxaphene levels were detected in the low ng g^{-1} (dry wt.) concentrations with maximum fluxes occurring the mid 1970s. Chlorobornane congener profiles in the sediment core slices consist of higher proportions of hexachlorobornane (Hx-Sed, B6-923) and heptachlorobornane (Hp-Sed, B7-1001). Both appear to be sediment dechlorination products of more highly chlorinated bornanes although they are minor constituents of technical toxaphene (Miskimmin, 1995; Stern, 1996). The presence of B6-923 and B7-1001 appears to be indicative of direct inputs of technical toxaphene into lake waters or streams within the watershed. The observed increase in toxaphene concentration in the core slice representing the early to mid 1950s may be the result of the 1950 Red River flood.

INTERPRETATION

Our interpretation of the core profiles is that they have recorded the chemical history of the lake for the last century or so. Cesium-137 peaks fell in the 1960s, the peak period of atmospheric nuclear bomb testing, when slice dates were assigned based on lead-210 profiles. The cesium-137 profiles have not fallen as quickly as they should have since the 1960s and the probable reason is input of Cs-137 from Atomic Energy of Canada's Whiteshell Nuclear Research Establishment on the Winnipeg River. Inputs of mercury to Lake Winnipeg have increased over the last century, although not greatly during the last 20 or 30 years; indeed, they may even have decreased during that time but not enough to have returned to levels typical of pre-European settlement. The inputs are too great to be explained by atmospheric fallout alone and are probably the result of human activities within the watershed. The situation is similar for lead, although the changes are smaller than with mercury. For cadmium, the cores do not reveal a clear trend over the past century. PAH profiles generally show sub-surface maxima like those from a number of other North American sites and suggest that current inputs are smaller than those in the middle years of the century. Toxaphene results parallel the history of usage of that compound with evidence of dechlorination to more stable components and of recent increases in inputs.

ACKNOWLEDGMENTS

We wish to acknowledge the field assistance of the Captain and crew of the CCGS *Namao* and to members of the Geological Survey of Canada, notably B.J. Todd, C.F.M. Lewis, L.H. Thorleifson and F. Jodrey and also to E. Neilsen from the Manitoba Department of Energy and Mines for site selection and for assistance with collection and on-board slicing of cores.

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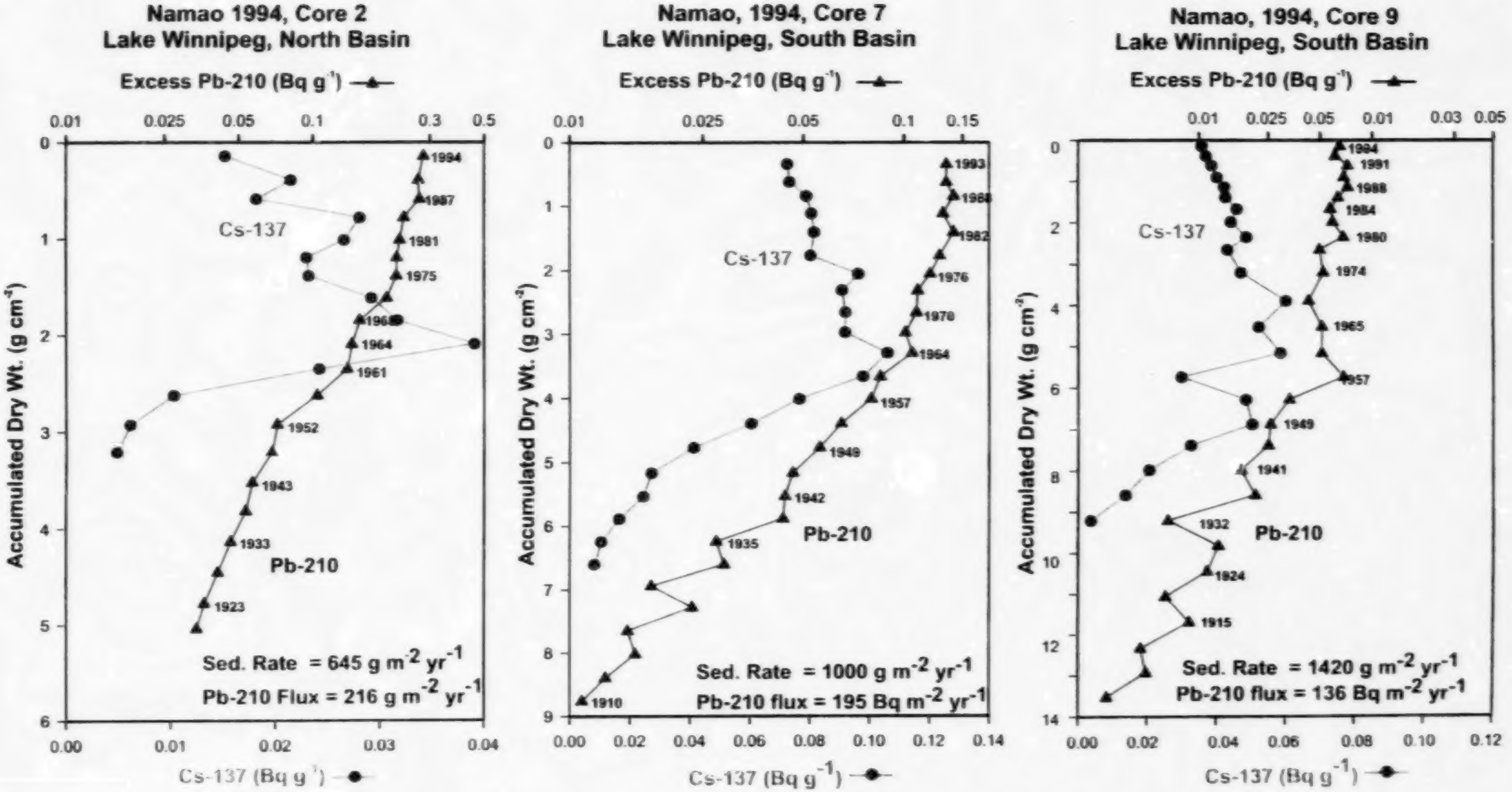

Figure 1. Down-core profiles of lead-210 and cesium-137 in cores 2, 7 and 9 from Lake Winnipeg, 1994.

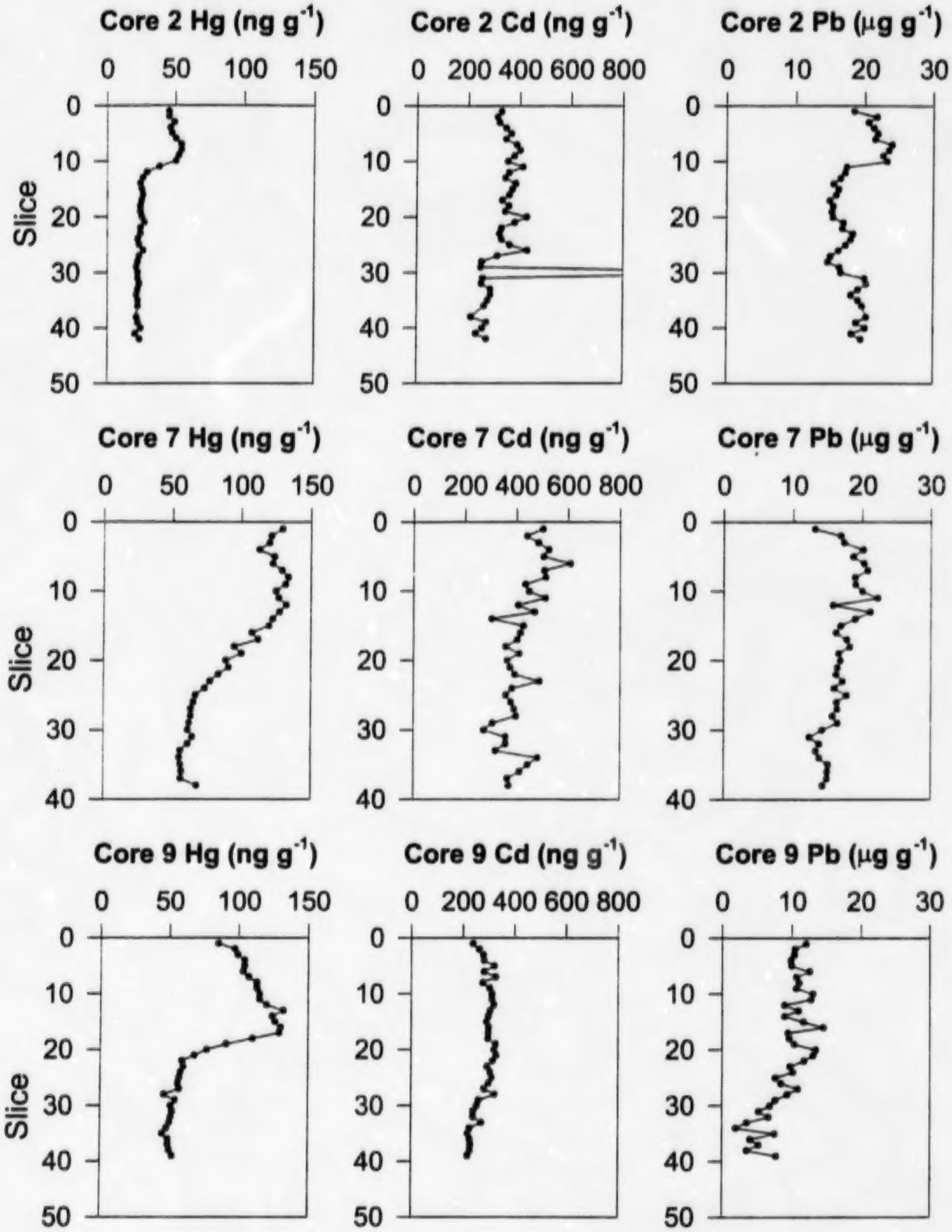

Figure 2. Profiles of mercury, cadmium (ng g^{-1} dry wt) and lead (µg g^{-1} dry wt) in cores 2, 7 and 9, 1994.

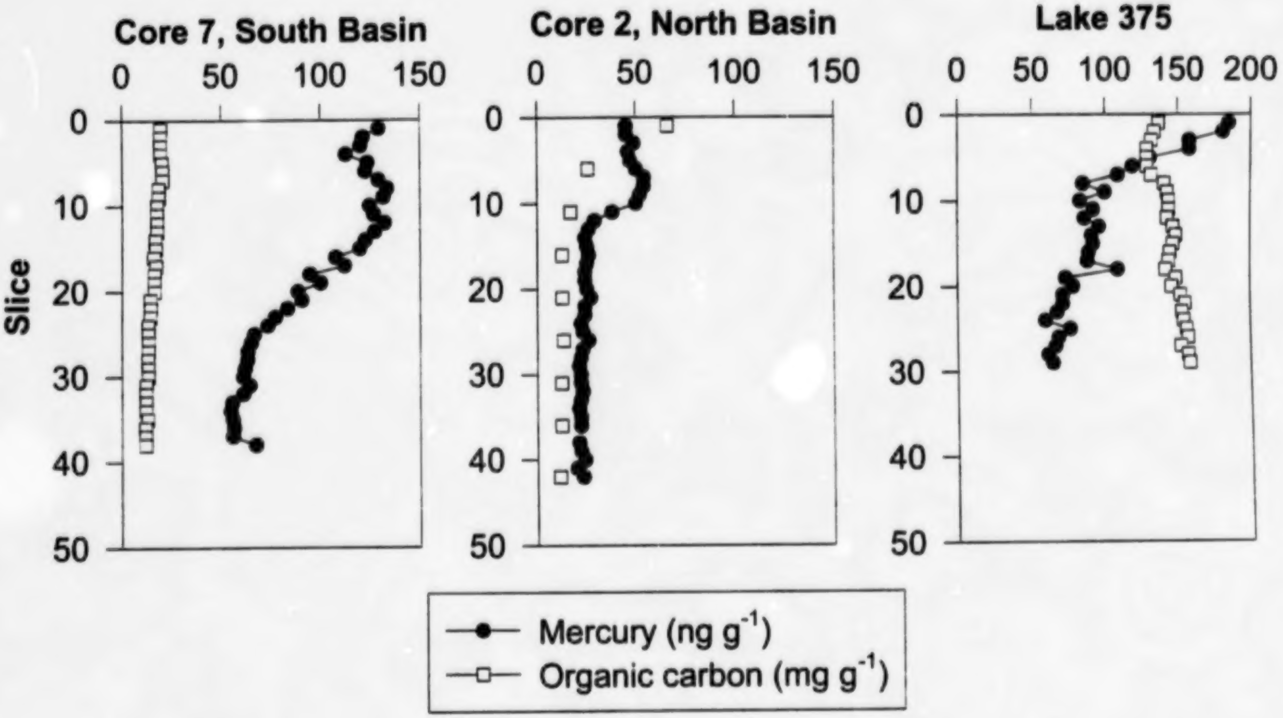

Figure 3. Mercury and organic carbon profiles, cores 7 and 2 from Lake Winnipeg and a core from Lake 375, Experimental Lakes Area, northern Ontario.

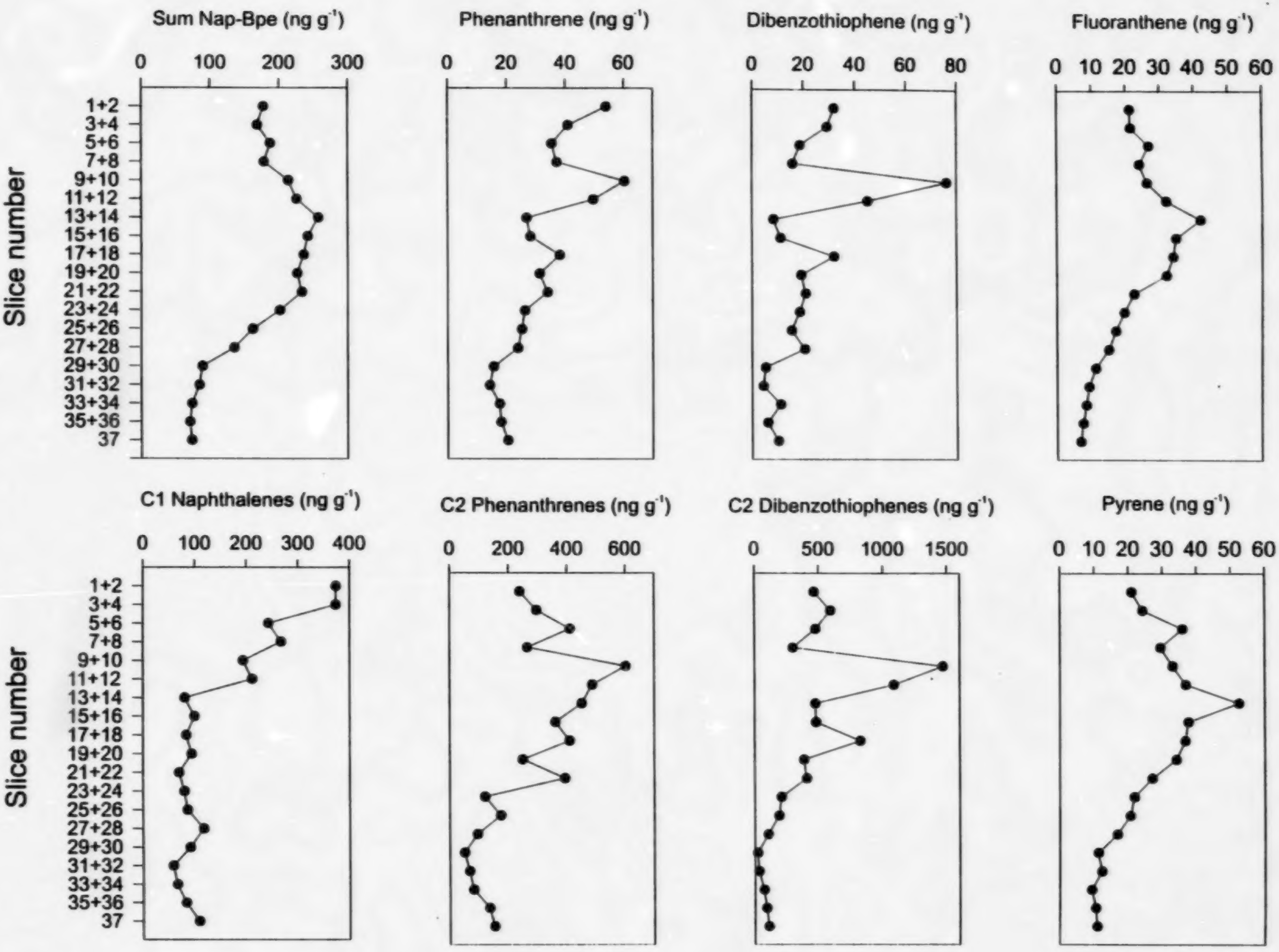

Figure 4. Polycyclic aromatic hydrocarbons in Lake Winnipeg sediment core 7.

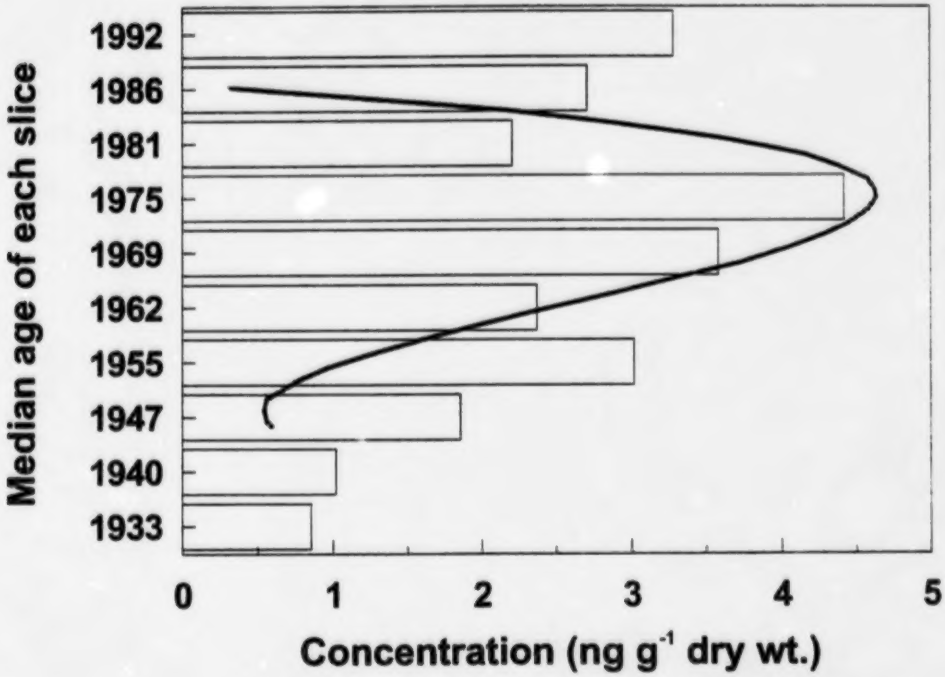

Figure 5. Toxaphene in dated layers of core 7 (slices were combined to obtain enough material to analyze.) The solid line represents the history of the use of toxaphene.

8. Biostratigraphy

8.1 Fossil diatoms of Lake Winnipeg, and comparison of diatoms in the Agassiz and Baltic basins

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ABSTRACT

Freshwater diatom taxa were found to dominate in 6 sediment cores and 10 surficial samples of Lake Winnipeg sediments. Minor occurrences of indifferent, to saline and brackish water diatom taxa were found. Chrysophyte stomatocysts, phytoliths and sponge spicules were relatively common. Diatom abundances were generally much lower than in adjacent Lake Manitoba. Barren sections typified glacial Lake Agassiz sediment.

The diatom abundance in sediments deposited in Lake Agassiz, Lake Winnipeg, Baltic Ice Lake and the Yoldia Sea are similarly low and scattered. This is explained by turbid conditions reducing the photic zone, i.e. the primary production, and a diluting effect in sediment caused by a high accumulation rate. In sediments of Lake Manitoba, diatom frustules are abundant, probably caused by an inflow of saline groundwater stimulating primary production. Sediments deposited in the Ancylus Lake and the Litorina Sea display relatively large amounts of diatoms, the former being an isolated freshwater lake and the latter a large brackish, marine bay of the Atlantic Ocean. This may be explained by an enhanced primary production. The environments of the Emerson Phase of Lake Agassiz and Ancylus Lake favoured several taxa in common, indicating similar water chemistry.

INTRODUCTION

The diatom content in ten surficial grab samples from Lake Winnipeg and in six sediment cores which also penetrate sediments of glacial Lake Agassiz is documented in this report (Fig. 1, Table 1). These samples were collected during Cruise 96-900 of CCGS *Namao* (Todd, this volume).

The diatom abundance in sediments accumulated in glacial meltwater lakes is normally low to barren. Despite this, even a sparse occurrence can sometimes reveal information about palaeoecological conditions. In this report, the occurrence of diatoms in the sediments of Lake Agassiz in North America (Fig. 2) and the Baltic Ice Lake in northern Europe (Fig. 3) is compared and discussed. Normally, diatoms are much more common in the sediments of large lakes isolated from ice margins, or in distal bays of proglacial lakes. The two largest post-glacial lakes succeeding glacial Lake Agassiz in southern Manitoba are Lake Manitoba and Lake Winnipeg; their sediments, which accumulated during the middle and late Holocene, reveal completely different histories regarding diatom content. This discrepancy is discussed and compared with the diatom content of sediments accumulated during various stages of the Baltic Sea.

Material and Methods

In this report, analysis of siliceous microfossils is presented from six sediment cores and ten surficial sediment samples collected in Lake Winnipeg (Fig. 1). At each coring site, the sediment cores were collected with a 9-m long Kullenburg-type piston corer (PC) for recovery of deeper sediment , and a complementary 2-m long gravity corer (GC) to ensure recovery of the uppermost lakefloor sediment (Lewis et al. this volume). Sediment types range from silty clay to silty clay mud in the cores. The surficial sediment types consisted of medium sand and silty clay mud. Siliceous microfossils were separated from the sediment using the technique described by Battarbee (1986). The floras of Mölder and Tynni (1967-1973), Tynni (1975-1980), Krammer and Lange-Bertalot (1986,1988,1991a, b) combined with publications by Camburn and Kingston (1986), Håkansson and Kling (1989), Kling and Håkansson (1988) and Risberg (1991) were used as an aid to identification and ecology. Information on diatoms from the sedimentary basins other than Lake Winnipeg were obtained from literature sources.

RESULTS AND DISCUSSION

Lake Winnipeg

A. Cores

From the 1996 cruise six sediment cores from the northern basin (201 PC, 201 GC, 204 PC, 204 GC, 205 PC, and 205

GC), and ten surficial sediment samples from both the northern and the southern basins were studied (Fig. 1, Table 1).

The cores 201 GC and 201 PC, offshore Grand Rapids, were studied in order to document the succession in the western part of the northern basin, and to possibly trace the onset of the diversion of the Saskatchewan River through Lake Winnipeg beginning about 4.7 ka (McMartin, this volume). Today the Saskatchewan river enters the northern basin from the west. However, after study of these cores began it was determined that the radiocarbon age of the basal sediment was 4800±70 BP (Telka, this volume), so all Lake Winnipeg sediment in this core post-dated the diversion. The diatom assemblages in the five samples analyzed from core 201GC resemble each other to a large extent. Dominating taxa in the two upper samples at 10 and 50 cm depth are *Aulacoseira islandica, A. ambigua and A. distans.* These species are somewhat less common in the lower three samples at 90, 130 and 170 cm depth. If anywhere, a stratigraphic boundary may be put at around 70 cm. In core 201 PC diatoms are sparse, except at 90 and 210 cm where *Aulacoseira ambigua* is common (Figs. 4, 5). Freshwater taxa dominate the sequence, while brackish water taxa and indifferent taxa are found mainly as fragments. This sequence displays very few stratigraphic changes, corroborating the radiocarbon evidence that the Saskatchewan River diversion occurred before the onset of mud accumulation in this core.

Sediments in cores 204GC and 204PC from the northeastern part of the northern basin, offshore Warren Landing, probably accumulated in Lake Winnipeg. Four samples were studied from core 204GC, at 50, 90, 130 and 170 cm depth. There seems to be a marked boundary between 90 and 130 cm. The two upper samples display low concentrations of diatoms while the two lower ones contain an abundance of frustules. Dominating taxa are *Stephanodiscus niagarae, Aulacoseira granulata* and *A. islandica.* These variations point to the fact that diatom production and/or preservation is very variable over time. Core 204PC may be divided into four siliceous microfossil assemblage zones (Figs. 6, 7). Zone 204PC-1 is probably dominated by *Aulacoseira islandica*; these frustules were observed in valve view making the identification uncertain. Phytoliths are relatively common (Fig. 6), inferring a strong influence from the surrounding land surface. Zone 204 PC-2 is characterized by very few diatom frustules. Zone PC 204-3 displays abundant *Aulacoseira islandica* and a few frustules of *Stephanodiscus medius* and S. *niagarae.* Zone 204 PC-4 represents a second sequence with low diatom content. The upper Zone 204 PC-5 contains abundant siliceous microfossils. Diatoms, *Stephanodiscus niagarae* and *Aulacoseira islandica,* and Chrysophyte stomatocysts dominate. Also, phytoliths are common. This change in abundance points to a drastic change in the environment and/or preservation conditions at the zone boundary 204 PC-4 and 204 PC-5.

The core 205 GC was only studied in one sample at 10 cm depth (Table 2). Several taxa of *Aulacoseira* spp. and *Stephanodiscus* spp. were found. This differs completely from core 205 PC where only two frustules of the freshwater taxon *Eunotia pectinalis* were found in twelve samples (Table 2). No other siliceous microfossils were observed. These observations may indicate that the sampled sediments in 205 PC accumulated in Lake Agassiz, while the 205 GC sample accumulated in Lake Winnipeg.

B. Modern samples

Most of the modern samples collected in nearshore locations contained abundant diatoms (Fig. 8). Two of the samples, George Island 310 and 311, consisted of pure fractions of medium sand; therefore, no siliceous microfossils were to be recovered. Although in low percentages, the number of brackish (e.g. *Melosira juergensii* and *Surirella brightwelli*) and halophilous taxa *(Gomphonema olivaceum* and *Rhoicopshenia abbreviata)* in these samples is more frequent compared to the sediment cores. An interesting observation is that different taxa of *Aulacoseria* dominate at different stations (Fig. 8), possibly indicating various degrees of eutrophication in Lake Winnipeg. For example, *A. granulata* dominate in the northern part of the North Basin (Spider Island and Grand Rapids samples) where human population is least.

In general, siliceous microfossil abundances were much lower compared to the Lake Manitoba sequence described later. Among diatoms, freshwater taxa dominate, complemented with minor occurrences of indifferent to saline, and brackish water taxa (Table 3). Chrysophyte stomatocysts and phytoliths were found in almost every sample. Sponge spicules were relatively common.

Stephanodiscus niagarae, which is the most common taxon in the Lake Manitoba sequence, occurs sporadically in Lake Winnipeg. In some cores it is even absent. The relatively many finds of phytoliths and aerophilous diatoms indicate that there has always been a strong influence from surrounding soils in the sediments of Lake Winnipeg.

Kling (1996) has studied the fossil and modern phytoplankton communities in Lake Winnipeg. As example *Stephanodiscus niagarae, S. binderanus, Aulacoseira islandica* and A. *subarctica* have been identified in uppermost sediments. In the southern basin of Lake Winnipeg, recent taxa like *Cyclotella meneghiniana, Stephanodiscus parvus and Cyclostephanos dubius* have been recorded indicating eutrophic and polluted conditions (Kling, 1996; *cf.* also Stoermer et al., 1987). *Stephanodiscus agassizensis* is mainly restricted to the southern basin where turbid, eutrophic and light limited conditions prevail. Compared to an investigation during the 1920s, it was concluded by Kling (1996) that several species were not to be found today. Instead, many more taxa typical of an increased eutrophication had developed. Spatial variability was explained by geology of the basin, influx from drainage areas and variation in climate between the northern and southern basin. Temporal variability was explained by year to-year variation in climate.

The Agassiz basin

Lake Agassiz

Lake Agassiz was formed about 11,800 ^{14}C years BP and drained finally after 8500 ^{14}C years BP. Caused by variations in the extension of the Laurentide Ice sheet and isostatic uplift, the lake experienced several changes in water depth, outflow routes and geographical distribution (Teller, 1995). New information from the Lake Winnipeg Project suggests Lake Agassiz persisted in the Lake Winnipeg basin until after 8000 14C years BP (Telka, this volume; Lewis et al., this volume).

The diatom flora of this giant proglacial lake is characterized by taxa indicating a variety of palaeoecological conditions. Normally, frustules found in nearshore locations indicate freshwater conditions (Ritchie and Koivo, 1975; Björck and Keister, 1983). This is expected since the lake water to a large extent emanated from meltwater of the Laurentide Ice Sheet. Finds of diatom taxa indicating brackish conditions, e.g. *Paralia sulcata*, have also been made (Risberg et al., 1996). This may be the result of input from saline ground water or dissolved mineral salts. At least locally, such input may have influenced the water chemistry. *Paralia sulcata* is a taxon that dislikes living in cold water (Long, 1997) and it can live both as a benthic and planktonic form (Stabell and Lange, 1990). It is therefore suggested that in certain areas of Lake Agassiz, shallow water depths with relatively warm water, in addition to saline groundwater input, allowed this species to grow.

The sparse occurrence of frustules in Lake Agassiz sediments can be attributed to unfavorable conditions in terms of high sediment load in the water. This would reduce the photic zone allowing no benthic species to thrive. The high sediment load also implies a high accumulation rate, diluting the diatom concentration. These conditions were probably more pronounced close to the ice margin, i.e. in sediments underlying Lake Manitoba and Lake Winnipeg sedimentary strata. Further south in Lake Agassiz, favorable local conditions seem to have allowed diatoms to grow in higher abundance (Björck and Keister, 1983).

The transgressive Emerson phase of Lake Agassiz, which in age is slightly younger than 10,000 ^{14}C yrs BP, is characterized at the Wampum site in southern Manitoba by species like *Aulacoseira islandica, Fragilaria* spp., *Gyrosigma attenuatum, Navicula tuscula* and *Stephanodiscus niagarae (*Risberg et al. in prep). This assemblage dominated partly by plankton overlies sediments dominated by epiphytic and benthic taxa like *Cymbella* spp., *Mastogloia smithii v. lacustris, Navicula vulpina, Neidium ampliatum* and *Stauroneis phoenicenteron.*

Lake Manitoba

In a 14-m long sediment core taken in the central part of the southern basin, the isolation of Lake Manitoba from Lake Agassiz has been determined partly by mineral magnetic characteristics and partly by diatom analysis (Risberg et al., in prep). These two methods indicate that there is a discrepancy in the order of 60 cm, where mineral magnetic parameters indicate a stratigraphically lower and thus earlier age, for this event. If the mineral magnetic record is correct, there is a time period after the isolation from Lake Agassiz when diatom growth and/or preservation were sparse in Lake Manitoba. This observation is plausible since environments in this oldest stage of Lake Manitoba likely would have been unfavorable for high primary production, owing to, possibly, a high sediment load. Eventually, at around 7600 ^{14}C years BP, the situation changed and for the rest of the Holocene diatoms thrived in the basin. Several stages of development were recorded in the stratigraphy, influenced by climate changes, differential isostatic uplift, input of the Assiniboine River, high salinity conditions and an increase in the trophic state.

The most characteristic taxon of Lake Manitoba during the main part of the Holocene is the freshwater planktonic *Stephanodiscus niagarae.* The Assiniboine River input, as one long or several short events between ca. 6000 and 4000 ^{14}C years BP, was deduced from a peak of *Aulacoseira granulata,* a species that thrives in the river (Hedy Kling, pers. comm.). The brackish water interval was interpreted from the occurrence of *Cyclotella quillensis, C. agassizensis, Diploneis smithii and Surirella peisonis.* In the upper part of the core *Fragilaria* spp. showed massive occurrences, probably resulting from natural and/or cultural eutrophication.

In the uppermost ca. 7 m of sediment in Lake Manitoba, diatoms occur in high frequencies. Even though the lake is large and experiences turbid conditions, and thus a high sediment load in the water column, diatoms seem to have thrived. Possibly, an input of saline groundwater may have stimulated diatom growth, as exemplified by *Surirella peisonis,* a taxon that is stimulated by enhanced values of SO_4^{2-} (Schmid, 1996).

The Baltic Basin

Baltic Ice Lake

This Baltic stage lasted between ca. 13,000, when the initial stages were formed in front of the receding continental ice, and 10,300 ^{14}C years BP (Brunnberg, 1995; Björck, 1995). The sediments of this proglacial lake are mainly composed of varved and homogenous clays and are generally poor in diatoms (Florin, 1977; Svensson, 1989). Typical diatoms recorded in the southeastern part of the basin are the planktonic taxa *Aulacoseira islandica, A. alpigena* and *Stephanodiscus rotula* (Kaballiene, 1995). Sometimes periphytic taxa such as *Fragilaria leptostauron v. martyi* occur. Diatom data suggest that the Baltic Ice Lake may be characterized as an oligotrophic, somewhat acid, freshwater body (Florin, 1977; Kabaillene, 1995). Based on the finds of a few brackish water taxa, the above interpretation does not exclude the possibility of a short-term input of brackish water. The paucity of diatoms is attributed to the high suspension of sediments in the water and a high rate of accumulation diluting the amount of frustules per volume unit (Kabaillene, 1995; Abelmann, 1985). High occurrences of *Aulacoseira islandica* in sediments accumulated on the west coast of Sweden have been used to identify sequences affected by the abrupt drainage of the Baltic Ice Lake (Miller, 1982).

Yoldia Sea

This stage lasted between ca. 10,300 and 9500 ^{14}C years BP (Björck, 1995). The main part of the Yoldia stage is characterized by freshwater. A more or less true marine stage existed only for a minimum of 100 years and a maximum of 200 calendar years (Björck et al., 1996; Wastegård and Schoning, 1997). The diatoms growing during this stage are to a large extent the same as those thriving in the Baltic Ice Lake. Eronen (1974) states that the "poverty of diatoms may be suggestive of a Yoldia Sea supporting very little marine life". Dominating diatoms were the planktonic taxa *Aulacoseira islandica* and *Stephanodiscus neoastraea* together with epiphytic genera like *Eunotia* spp. and *Pinnularia* spp. Brackish-marine diatoms lived, especially in the western parts, during the most pronounced inflow of marine waters. This took place across the Närke Strait of southern Sweden whose low elevation at the time was the result of intense isostatic depression associated with the preceding glaciation. Among planktonic species, this brackish-marine stage is represented by *Actinocyclus ehrenbergii, Coscinodiscus excentricus, Grammatophora oceanica, Hyalodiscus scoticus and Rhabdonema* spp. Benthic and epiphytic taxa are represented by e.g. *Nitzschia punctata, Diploneis smithii* and *Mastogloia smithii* (Robertsson, 1990, 1995). In nearshore conditions, at least on the western side of the basin, these brackish-marine species were replaced by halophilous taxa like *Cocconeis pediculus* and *Rhoicosphenia abbreviate* (Möller and Stålhös, 1969; Hedenström, 1996). Both these taxa are also reported to thrive in freshwater basins where strong alkaline conditions prevail (Hustedt, 1959; Cholnoky, 1968). Therefore, caution should be taken when interpreting salinity variations relying solely on these species (cf. Sandgren et al., in press).

On the eastern side of the Baltic basin, the nature of the Yoldia Sea is more complicated. According to Raukas (1995) it is possible that brackish water never reached the eastern part. Re-depositional processes from Eemian sediments may explain the occurrence of brackish water or marine diatoms in Yoldia Sea sediments. From the Tallinn area, however, Lepland et al. (1995) have demonstrated that pronounced brackish water conditions prevailed during the Yoldia Sea.

Ancylus Lake

This freshwater lake phase lasted from ca. 9500 to 8300 ^{14}C years BP and was formed when the connection through the Närke Straits dried up (Björck, 1995). The chemistry of the lake water was somewhat enhanced in total dissolved solids meaning that, besides strict freshwater taxa, species indifferent to salinity could grow. Usually, there is a marked increase in diatom abundance compared to the Yoldia Sea stage. Examples of the freshwater taxa are *Ellerbeckia* *arenaria, Aulacoseira islandica, Stephanodiscus neoastraea, Diploneis domblittensis, D. maulerii, Gyrosigma attenuatum, Gomphocymbella ancylii and Fragilaria leptostauron v. leptostauron* (Eronen, 1974; Risberg, 1991; Hedenström, 1996; Risberg *et al.*, 1996; Robertsson, 1997). As examples of frequently occurring indifferent taxa *Epithemia* spp. and *Amphora ovalis* can be mentioned (Eronen, 1974).

Litorina Sea

When the main post-glacial eustatic rise in sea level flooded the thresholds in the Öresund Straits and in the Danish Straits, the water in the Baltic basin again became brackish. Maximum salinity occurred sometime between 7000 and 5000 ^{14}C years BP (Westman and Sohlenius, in press). In the planktonic diatom community *Coscinodiscus* spp., *Chaetoceros* spp., *Achnanthes taeniata, Grammatophora oceanica, Hyalodiscus scoticus* and *Melosira westii* were present (Alhonen, 1971; Eronen 1974; Miller 1986). Present day Baltic Sea is characterized by e.g. *Thalassiosira baltica, Actinocyclus octanarius, Coscinodiscus asteromphalus, Chaetoceros* spp., *Cyclotella striata, Rhizosolenia calcar avis,* and *Paralia sulcata* (Miller and Risberg, 1990; Risberg, 1990; Sakson and Miller, 1993; Andrén, 1994). There have been several transgressions during the Litorina Sea stage, which have resulted in varying salinity and water depths (Hyvärinen, 1980; Miller and Robertsson, 1981; Miller and Hedin, 1988; Risberg, 1991; Björck et al., 1994; Jantunen, 1995). Normally, the sediments accumulated in the Litorina Sea carry an abundance of diatoms. In some nearshore places, brackish water lagoons were formed during the mainly regressive shore displacement. These offered environments extremely suitable for diatom growth. Mass occurrences of e.g. *Fragilaria* spp. and *Campylodiscus clypeus* has been recorded (Miller, 1986).

GENERAL DISCUSSION

The main factors controlling preservation of diatom frustules are pH, temperature, coarseness of sediment, grazing and bioturbation, water depth, exposure, and undersaturation with respect to silica (Conley, 1988; Stoermer et al. 1991; Barker, 1992; Stoermer ,1993; Flower, 1993; Gasse et al,. 1997). From investigations in the Gotland Basin in the Baltic Sea, Grönlund (1993) states that dissolution of diatom frustules can vary through time and result in large variations in the diatom stratigraphy of a sediment core.

In this report, the diatom composition has been described for a variety of late glacial and post-glacial large basins. The sediments of Lake Winnipeg, at least in the northern basin, seem to show similarities with Lake Agassiz and the Baltic Ice Lake when comparing diatom abundance. The paucity of frustules can probably be related to turbid conditions keeping sediments in suspension for long periods. Since diatoms require light for their growth, this will restrict the primary production. An observation in favor of low primary production over chemical dissolution is the relatively large abundance of phytoliths in the sediments of Lake Winnipeg. These micro-particles of terrestrial and/or telmatic origin also consist of amorphous silica (e.g. Blackwell, 1971) and occur in almost all of the samples analyzed. The lack of weathering features on the observed diatom frustules also supports this statement.

Why then do the sediments of Lake Manitoba contain abundant diatoms? Here, turbid conditions (Kenney, 1985) and thus a shallow photic zone also characterize this basin. Lake Manitoba is situated within the northern Great Plains stretching from the Precambrian shield east of Lake Winnipeg to the Rocky Mountain foothills in the west. This area contains a large number of saline lakes (Last, 1992). One possible explanation may be that enhanced salinity conditions in Lake Manitoba has stimulated the primary production and thus the sedimentation and accumulation of frustules. Lake Winnipeg, located on the western edge of the Precambrian shield, may receive a much-reduced input of saline ground water (Betcher and Buhay, 1996). This statement is verified from the low numbers of brackish water and halophilous diatoms recorded in the sediments of Lake Winnipeg. That brackish to slightly brackish conditions may stimulate diatom growth is verified from a number of basins being isolated from a marine environment. Mass occurrence of *Fragilaria* spp. has, for example, been observed in basins on the west coasts of Belgium (Denys, 1990) and Norway (Stabell, 1985a, b) and also in basins in the process of being isolated from the Litorina Sea stage of the Baltic (Miller and Robertsson, 1981; Risberg, 1991). The latter type of basins may also contain species like *Campylodiscus clypeus, Nitzschia scalaris* and *Surirella striatula* in large amounts (Hyvärinen, 1984; Miller, 1986). This type of diatom flora has also been observed in lagoons isolated from a brackish water stage in the Baltic basin of pre-Welchsellan age, i.e. the Eemian, in Finnish basins (Grönlund, 1991).

In some areas of Lake Agassiz, especially during the Emerson transgressive phase, diatoms seem to have grown in relatively high frequencies. When doing so, the assemblages show large similarities with those representative of the Ancylus Lake stage of the Baltic basin. It seems that the water chemistries of these water bodies were similar. Salinity concentrations during the most pronounced brackish water interval in Lake Manitoba were probably similar to those of the Litorina Sea; however other ions such as $S0_4^{2-}$ were dominating.

The variations of different taxa dominating surface samples in Lake Winnipeg may be attributed to variations in climate, trophic state, geological setting conditions and/or influxes from the drainage area. Currents and wave-induced turbulence along the bottom may also contribute to the accumulation of various frustules over time. This component has been interpreted as being of minor importance in deep basins in the Baltic Sea and in the Gulf of Finland by Hällfors and Niemi (1975) where water depths range from 47 to 190 m. Water depth in Lake Winnipeg is in the order of 10 to 20 in indicating that wave action could more easily influence bottom conditions.

CONCLUSIONS

- The diatom abundance in sediments deposited in Lake Agassiz, Lake Winnipeg, the Baltic Ice Lake and the Yoldia Sea is equally low. This is explained by turbid conditions reducing the photic zone, and thus the primary production. Turbid conditions also lead to a diluting effect in the sediment caused by high accumulation rates

- In sediments deposited in Lake Manitoba, diatom frustules are abundant, probably caused by an inflow of saline ground water stimulating primary production, despite the turbid conditions in the photic zone.

- Sediments deposited in the Ancylus Lake and the Litorina Sea display relatively large amounts of diatoms, probably because the primary production was enhanced.

- The environments during the Emerson Phase of Lake Agassiz and the Ancylus Lake favoured several similar diatom taxa, indicating similar water chemistry and turbidity conditions.

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FIGURES

Fig. 1. Lake Winnipeg with the locations of the analysed sediment cores and grab samples.

Fig. 2. Map showing the maximum extension of Lake Agassiz and the locations of its large post-glacial remnants, Lake Manitoba and Lake Winnipeg (simplified after Teller 1987).

Fig. 3. Maps showing the general outlines of the configuration of the main stages during the postglacial development of the Baltic basin. A. Baltic Ice Lake, *ca.*11,000 ^{14}C yrs BP, just after the drainage at Mt. Billingen. B. The Yoldia Sea, *ca.* 10,000-9900 ^{14}C yrs BP. C. The Ancylus Lake *ca.* 9300-9200 ^{14}C yrs at the culmination of the transgression. D. The Litorina Sea, *ca.* 6500 ^{14}C yrs BP. (maps A, B and C simplified after Björck 1995, map D simplified after Lindström *et al.* 1991).

Fig. 4. Main groups of siliceous microfossils in the sediment core 201PC. Bars show the number of particles observed in five traverses on one slide at x400 magnification. + = a half or one frustule observed.

Fig. 5. Diatoms and their grouping according to salinity preferences in the sediment core 201PC. Bars show the number of frustules observed in five traverses at x400 magnification. B. = Brackish water taxa. A. = Aerophilous taxa. Unkn. = Unknown ecology. + = a half or one frustule observed. Dated material consists of charred spruce needles.

Fig. 6. Siliceous microfossils in the sediment core 204PC. Bars refer to the number of particles observed in five traverses at x400 magnification. The sample at 10 cm was counted in six traverses and the sample at 90 cm was counted at x 1000 magnification. + = a half or one frustule observed. Note different scales on x-axes.

Fig. 7. Diatoms and their grouping according to salinity preferences in the sediment core 204PC. Bars refer to the number of frustules observed in five traverses at x400 magnification. The sample at 10 cm was counted in six traverses and the sample at 90 cm was counted at x1000 magnification. B. = Brackish water taxa. Indiff. = Indifferent taxa. Aero. = Aerophilous taxa. Unkn. = Unknown ecology. + = a half or one frustule observed. Note different scales on x-axes. The upper dated material consists of ostracodes, and the lower one of a spruce needle fragment.

Fig. 8. Selected freshwater taxa on percentage bases in samples collected at eight stations in Lake Winnipeg. George Isl = George Island 313. Spider Isl = Spider Island 320. Gr. R. 316 = Grand Rapids 316. Gr. R. 317 = Grand Rapids 317. Willow Pt = Willow Point 326. Gimli = Gimli 304. Gr. Beach = Grand Beach 327. Balaton = Balaton 324.

Table 1. Modern nearshore samples analyzed for diatom content						
Area	**Sample No.**	**Site**	**Latitude N**	**Longitude W**	**Water Depth m**	**Sediment**
N. Basin	320	Spider Islands	53° 28.1'	97° 44.42'	11.4	Gritty mud
N. Basin	317	Grand Rapids	53° 12.45'	99° 13.93'	9.7	Silty pebbly sand
N. Basin	316	Grand Rapids	53° 12.42'	99° 13.84'	10.5	Clayey silt mud
N. Basin	313	George Island	52° 48.64'	97° 37.52'	13.3	Silty clay
N. Basin	311	George Island	52° 48.95'	97° 37.65'	5.1	Fine-medium sand
N. Basin	310	George Island	52° 49.0'	97° 37.67'	2.7	Medium sand
S. Basin	324	Balaton	50° 56.94'	96° 56.57	3.3	Silty mud
S. Basin	304	Gimli	50° 38.01'	96° 58.38'	6.1	Silty clay mud
S. Basin	326	Willow Pt.	50° 36.95'	96° 57.62'	6.3	Soft mud
S. Basin	327	Grand Beach			7.1	Mud

Table 2. Diatom counts for cores 204GC and 205PC.

Core 204 GC.

Depth (cm):	50	90	130	170	
Brackish water taxon					
Diploneis smithii		1	--	--	--
Indifferent taxon					
Mastogloia smithii v. lacustris	--	--	--	--	
Freshwater taxa					
Aulacoseira ambigua	--	--	8	--	
Aulacoseira distans	--	--	--	--	
Aulacoseira granulata	--	--	130	--	
Aulacoseira islandica	--	2	93	53	
Cyclotella radiosa		--	--	--	--
Eunotia pectinalis		--	--	--	--
Pinnularia spp.	f	f	--	f	
Stephanodiscus medius	--	--	9	--	
Stephanodiscus niagarae	--	--	47	10.5	
Aerophilous taxa					
Hantzschia amphioxys	0.5	--	--	--	
Pinnularia borealis		--	0.5	--	--
Chrysophyceae styomatocysts	10	8	9	46	
Phytoliths	8	4	3	15	
Sponge spiculae	2.5	2.5	--	2	
Starch grains	--	--	--	--	
Number of traverses:	5	5 x1000	1	5	

Core 205 PC.

Depth (cm):	90	130	170	210	250	290	330	370	410	450	490	520	
Freshwater taxon													
Eunotia pectinalis		--	--	--	--	--	--	--	2	--	--	--	--
Starch grains	--	--	1	--	--	--	--	--	--	--	--	--	
Number of traverses:	5	5	5	5	5	5	5	5	5	5	5	5	

Table 3. Compilation of diatoms identified in six sediment cores and ten grab samples from Lake Winnipeg. Taxa are grouped according to salinity preferences.

Brackish water taxa

Anomoeoneis sphaerophora (Ehrenberg) Pfitzer
Diploneis smithii (Brébisson) Cleve
Fragilariafasciculata (Agardh) Lange-Bertalot
Melosira juergensii Agardh
Nitzschia levidensis (W. Smith) Grunow
Surirella brightwelli W. Smith

Halophilous taxa

Gomphonema olivaceum (Homemann) Brébisson
Rhoicosphenia abbreviate (Agardh) Lange-Bertalot

Indifferent taxa

Amphora inariensis Krammer
Amphora libyca Ehrenberg
Cocconeis pediculus Ehrenberg
Cocconeis placentula Ehrenberg
Cocconeis placentula v. *klinoraphis* Geitler
Epithemia adnata (Kützing) Brébisson
Epithemia frickei Krammer
Epithemia turgida (Ehrenberg) Kützing
Epithemia turgida v. *granulata* (Ehrenberg) Brun
Fragilaria brevistriata Grunow
Fragilaria construens v. binodis (Ehrenberg) Hustedt
Fragilaria lapponica Grunow
Fragilaria pinnata Ehrenberg
Mastogloia smithii v. *lacustris Grunow*
Nitzschia sinuata (Thwaites?) Grunow
Rhopalodia gibba (Ehrenberg) O. Müller

Freshwater taxa

Aulacoseira ambigua (Grunow) Simonsen
Aulacoseira distans (Ehrenberg) Simonsen
Aulacoseira granulata (Ehrenberg) Simonsen
Aulacoseira islandica (O. Müller) Simonsen
Aulacoseira italica (Ehrenberg) Simonsen
Aulacoseira spp. Thwaites
Cyclotella ocellata Pantocsek
Cyclotella radiosa (Grunow) Lemmermann
Cyclotella sielligera Cleve & Grunow
Cymbella caespilosa (Kützing) Brun
Cymbella cf. gibba Bailey
Cymbella prostrata (Berkeley) Cleve
Diatoma vulgaris v. *distorta* Bory
Diploneis elliptica (Kützing) Cleve
Eunotia intermedia (Krasske) Nörpel & Lange-Bertalot
Eunotia pectinalis (Dillwyn) Rabenhorst
Eunotia spp. Ehrenberg
Fragilaria capucina Desniazières
Fragilaria exigua Grunow
Fragilaria leptostauron v. *martyi* (Héribaud) Lange-Bertalot

Fragilaria ulna (Nitzsch) Lange-Bertalot

Frustulia rhomboides (Ehrenberg) De Toni

Gomphonema angustatum (Kützing) Rabenhorst

Gomphonema clavatum Ehrenberg

Gomphonema grovei v. *lingulatum* (Hustedt) Lange-Bertalot

Gyrosigma acuminatum (Kützing) Rabenhorst

Gyrosigma attenuatum (Kützing) Rabenhorst

Navicula cuspidata (Kützing) Kützing

Navicula elginensis (Gregory) Ralfs

Navicula platystoma Ehrenberg

Navicula pseudanglica Lange-Bertalot

Navicula radiosa Kützing

Navicula scutelloides W. Smith

Neidium ampliatum (Ehrenberg) Krammer

Nitzschia angustata Grunow

Pinnularia gibba Ehrenberg

Pinnularin microstauron (Ehrenberg) Cleve

Pinnularia nodosa Ehrenberg

Pinnularia spp. Ehrenberg

Stauroneis anceps Ehrenberg

Stephanodiscus medius Håkansson

Stephanodiscus niagarae Ehrenberg

Surirella brebissoni Krammer & Lange-Bertalot

Tabellaria fenestrata (Lyngbye) Kützing

Tabellaria sp. Ehrenberg

Aerophilous taxa

Eunotia bilunaris (Ehrenberg) Mills

Hantzschia amphioxys (Ehrenberg) Grunow

Pinnularia borealis Ehrenberg

Unknown ecology

Cymbella sp. Agardh

Diploneis sp. Ehrenberg

Entomoneis sp. Ehrenberg

Fragilaria spp. Lyngbye

Gyrosigma sp. Hassall

Navicula spp. Bory

Nitzschia sp. Hassall

Varia

Other siliceous microfossils

Chrysophyceae stomatocysts

Phytoliths

Sponge spiculae

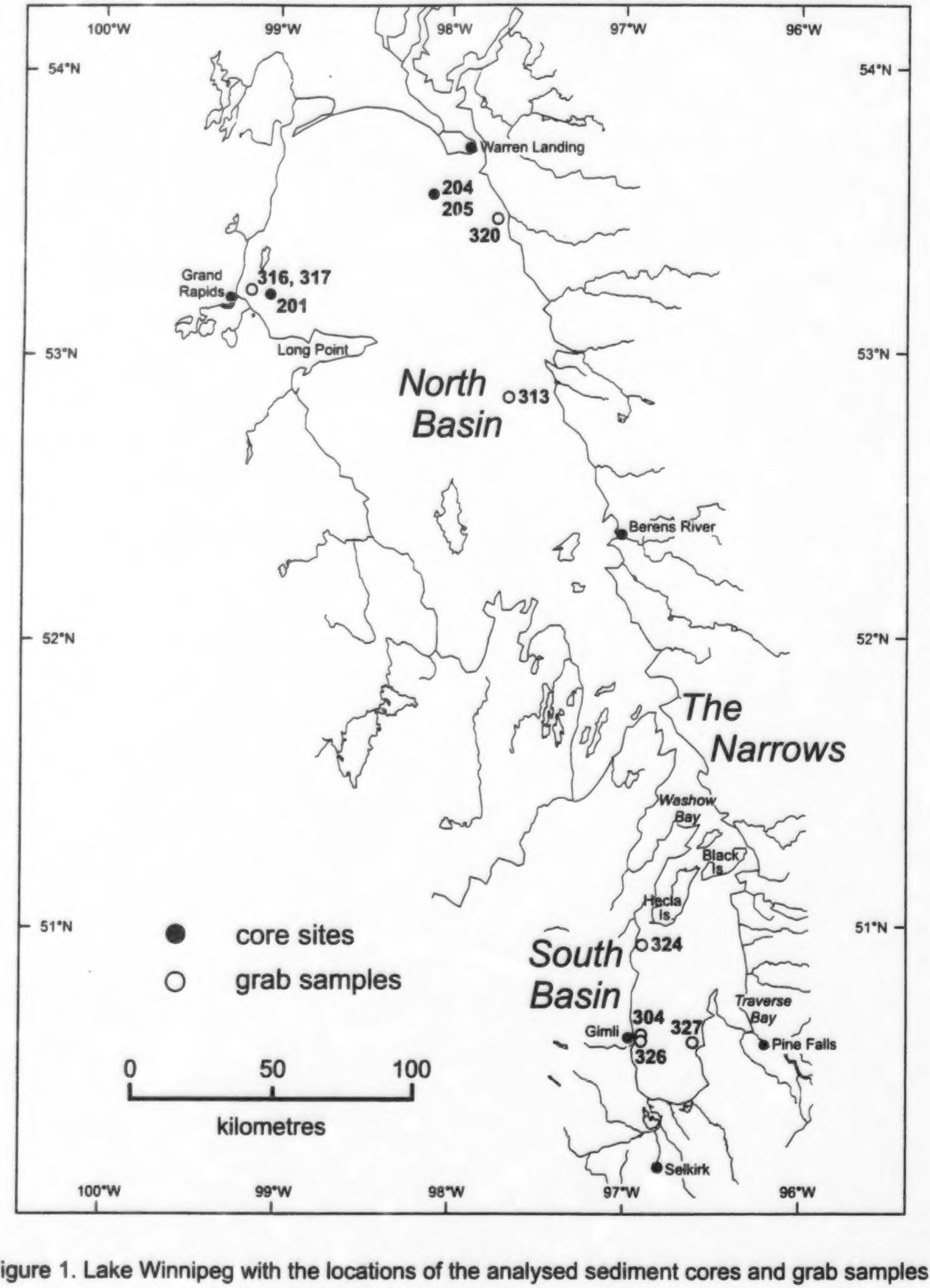

100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
Warren Landing
204
205
320
Grand Rapids
316, 317
201
Long Point
North Basin
313
Berens River
The Narrows
Washow Bay
Black Is.
Hecla Is.
324
South Basin
304
Gimli
327
326
Traverse Bay
Pine Falls
Selkirk
● core sites
○ grab samples
0
50
100
kilometres

Figure 1. Lake Winnipeg with the locations of the analysed sediment cores and grab samples.

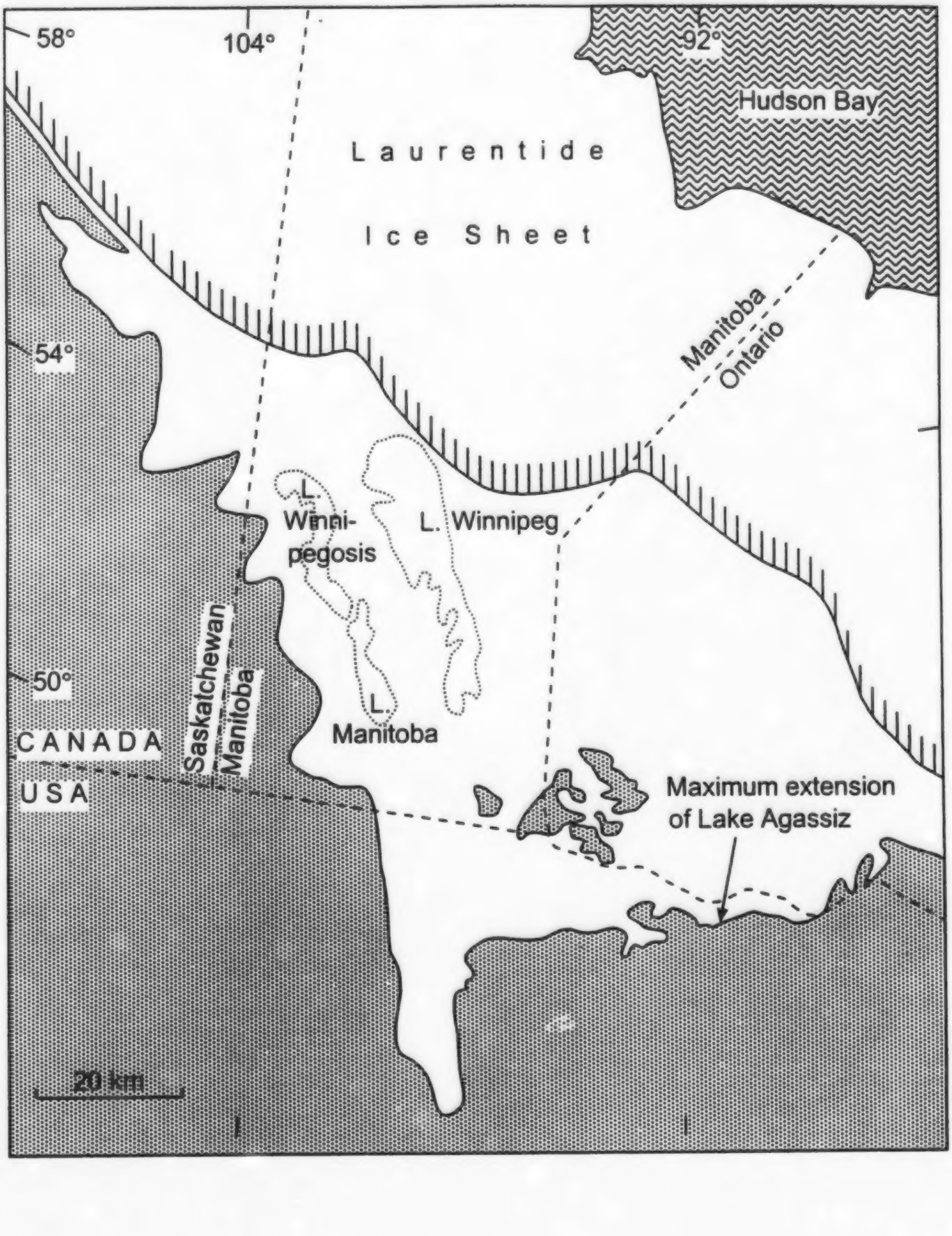

58°
104°
92°
Hudson Bay
Laurentide
Ice Sheet
Manitoba
Ontario
54°
L. Winnipegosis
L. Winnipeg
50°
L. Manitoba
CANADA
USA
Saskatchewan
Manitoba
Maximum extension of Lake Agassiz
20 km

Figure 2.

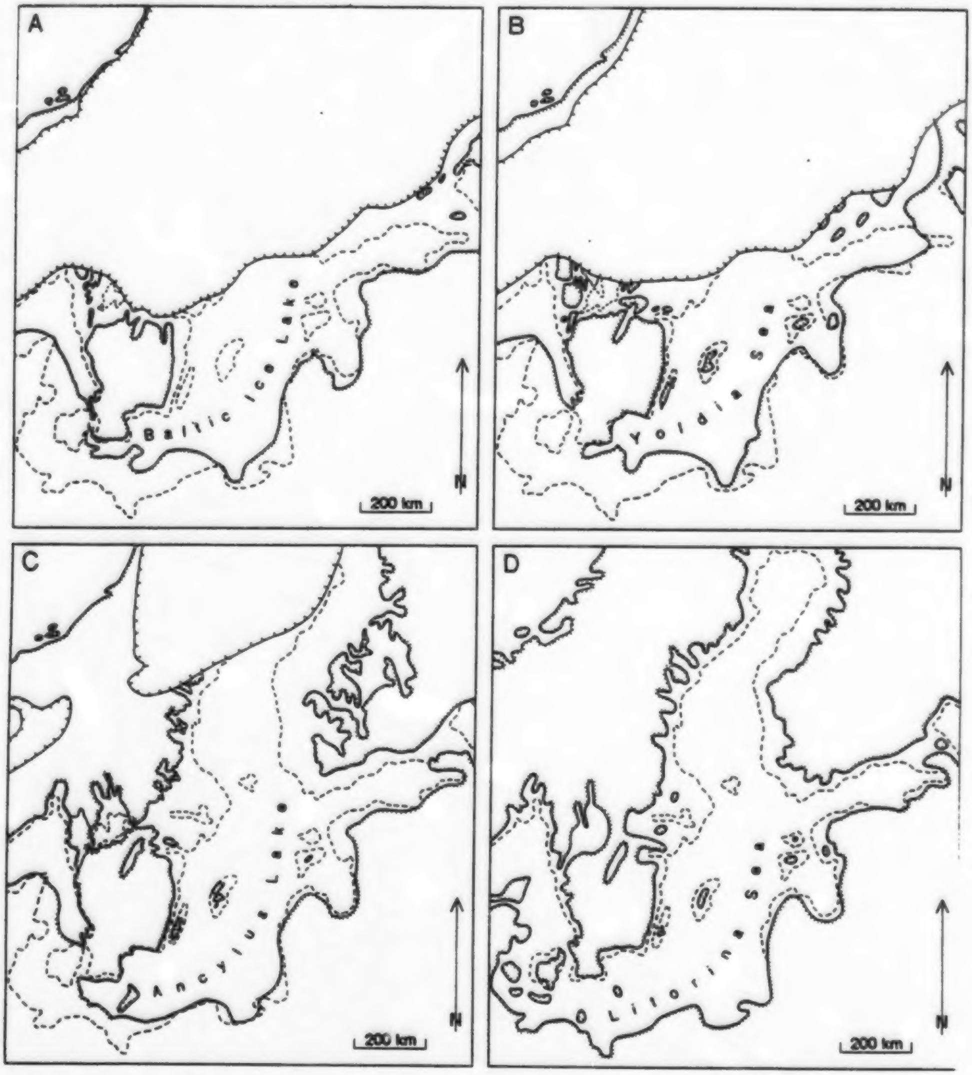
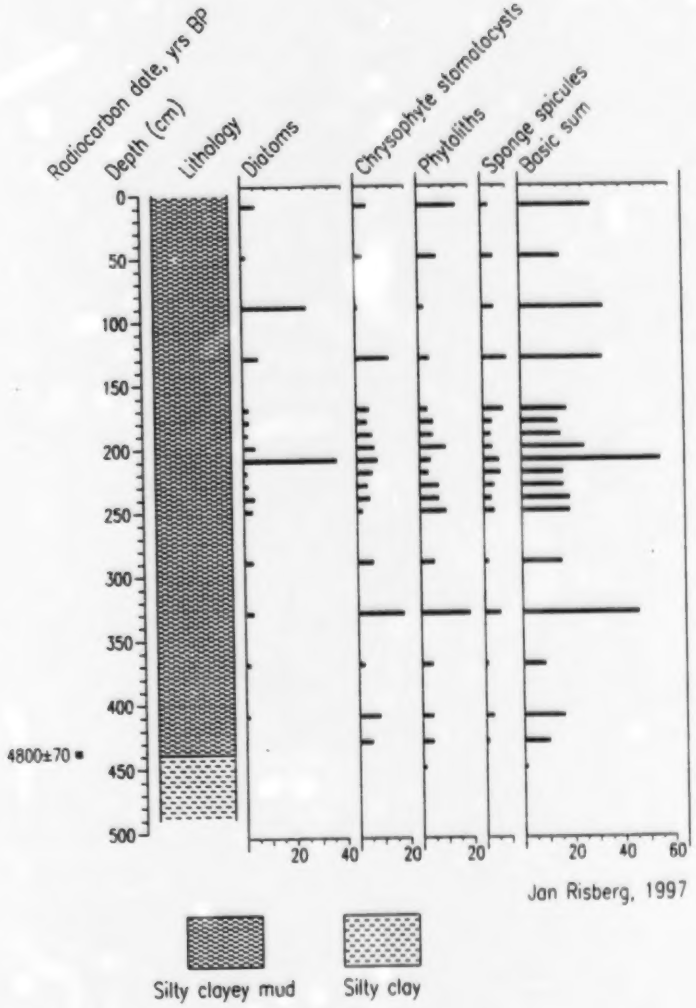

A
Baltic Ice Lake
200 km
N
B
Yoldia Sea
200 km
N
C
Ancylus Lake
200 km
N
D
Litorina Sea
200 km
N

Figure 3.



Jan Risberg, 1997

Figure 4.

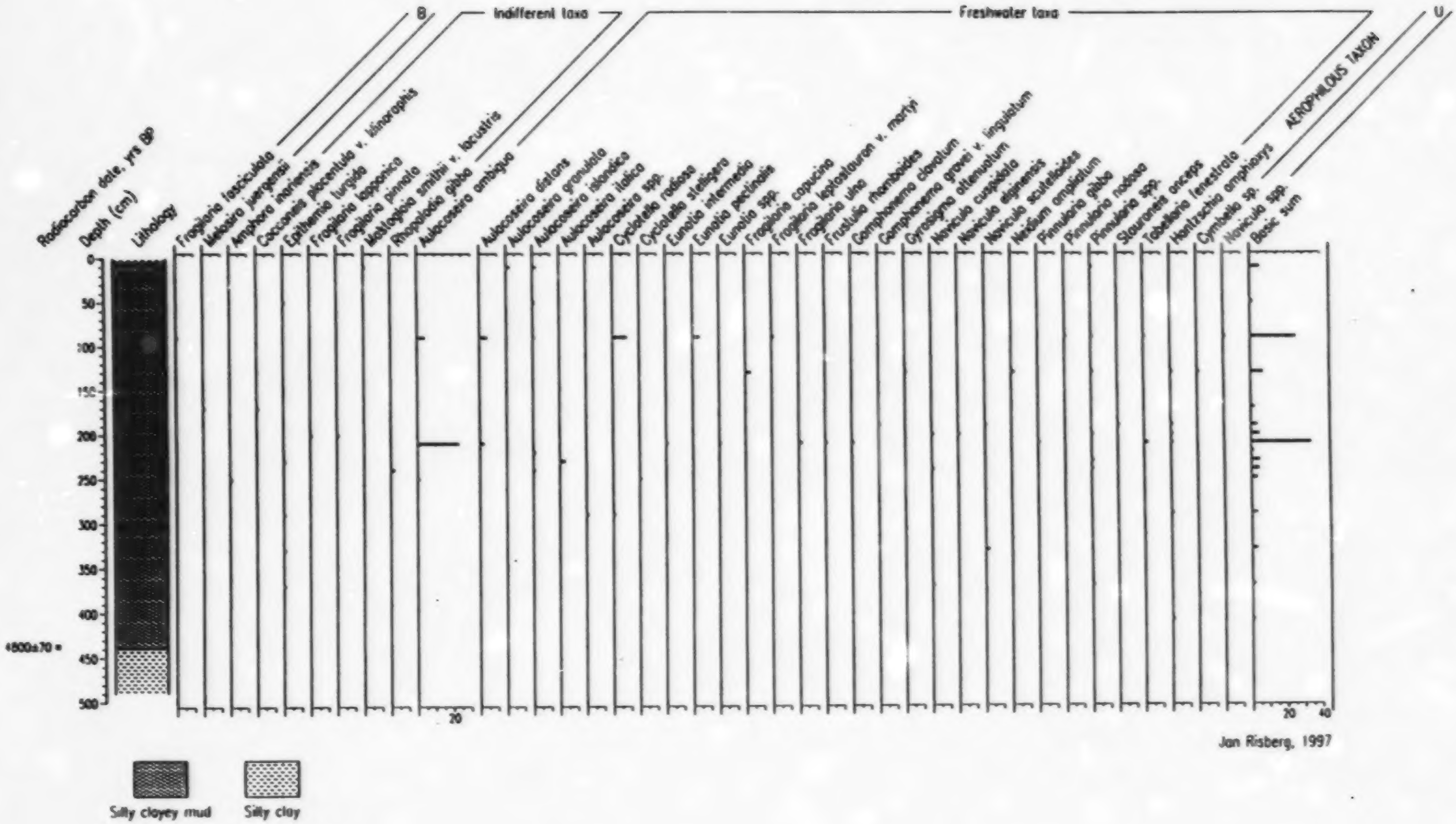

Radiocarbon date, yrs BP
Depth (cm)
Lithology
Fragilaria fasciculata
Melosira juergensii
Amphora inariensis
Cocconeis placentula v. klinoraphis
Epithemia turgida
Fragilaria lapponica
Fragilaria pinnata
Mastogloia smithii v. lacustris
Rhopalodia gibba
Aulacoseira ambigua
Aulacoseira distans
Aulacoseira granulata
Aulacoseira islandica
Aulacoseira italica
Aulacoseira spp.
Cyclotella radiosa
Cyclotella stelligera
Eunotia intermedia
Eunotia pectinalis
Eunotia spp.
Fragilaria capucina
Fragilaria leptostauron v. martyi
Fragilaria ulna
Frustulia rhomboides
Gomphonema clavatum
Gomphonema gravei v. lingulatum
Gyrosigma attenuatum
Navicula cuspidata
Navicula digmensis
Navicula scutelloides
Neidium ampliatum
Pinnularia gibba
Pinnularia nodosa
Pinnularia spp.
Stauroneis anceps
Tabellaria fenestrata
Hantzschia amphioxys
Cymbella sp.
Navicula spp.
Basic sum
B
Indifferent taxa
Freshwater taxa
U
AEROPHILOUS TAXON
0
50
100
150
200
250
300
350
400
450
500
4800±70
20
20
40
Jan Risberg, 1997
Silty clayey mud
Silty clay

Figure 5.

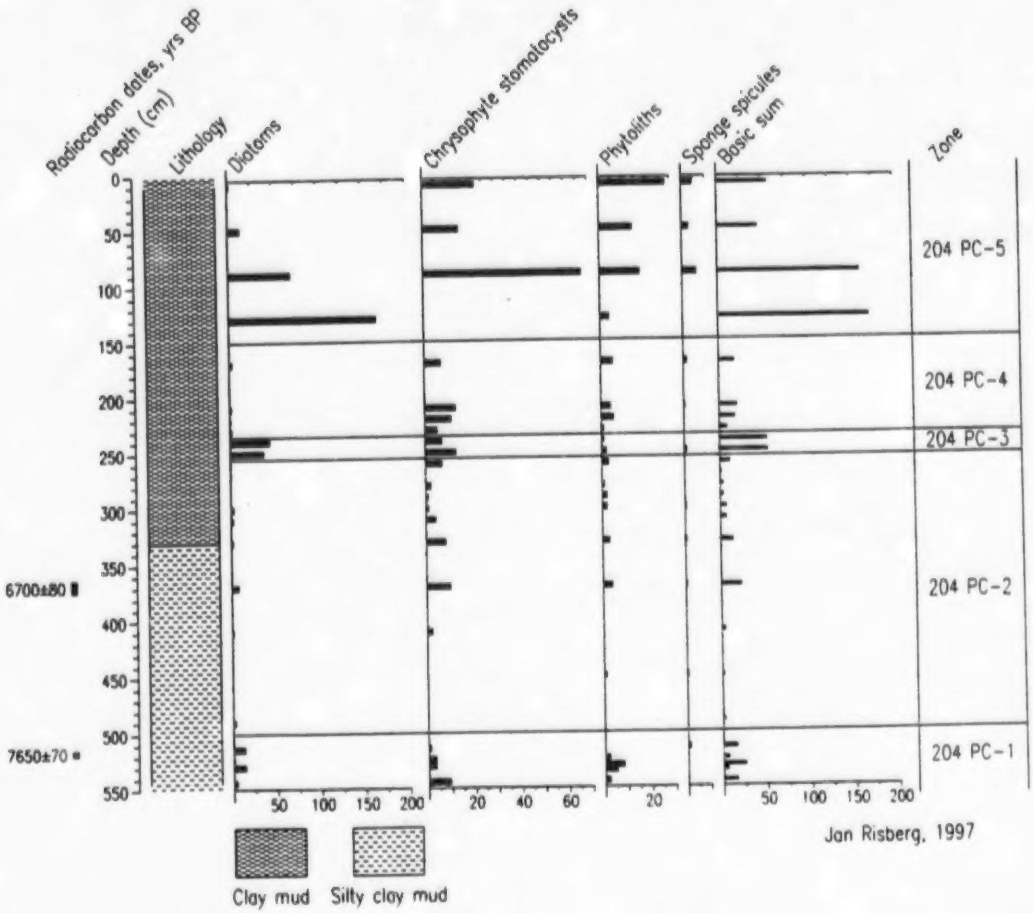

Radiocarbon dates, yrs BP
Depth (cm)
Lithology
Diatoms
Chrysophyte stomatocysts
Phytoliths
Sponge spicules
Basic sum
Zone
0
50
100
150
200
250
300
350
400
450
500
550
6700±80
7650±70
204 PC-5
204 PC-4
204 PC-3
204 PC-2
204 PC-1
50
100
150
200
20
40
60
20
50
100
150
200
Jan Risberg, 1997
Clay mud
Silty clay mud

Figure 6.

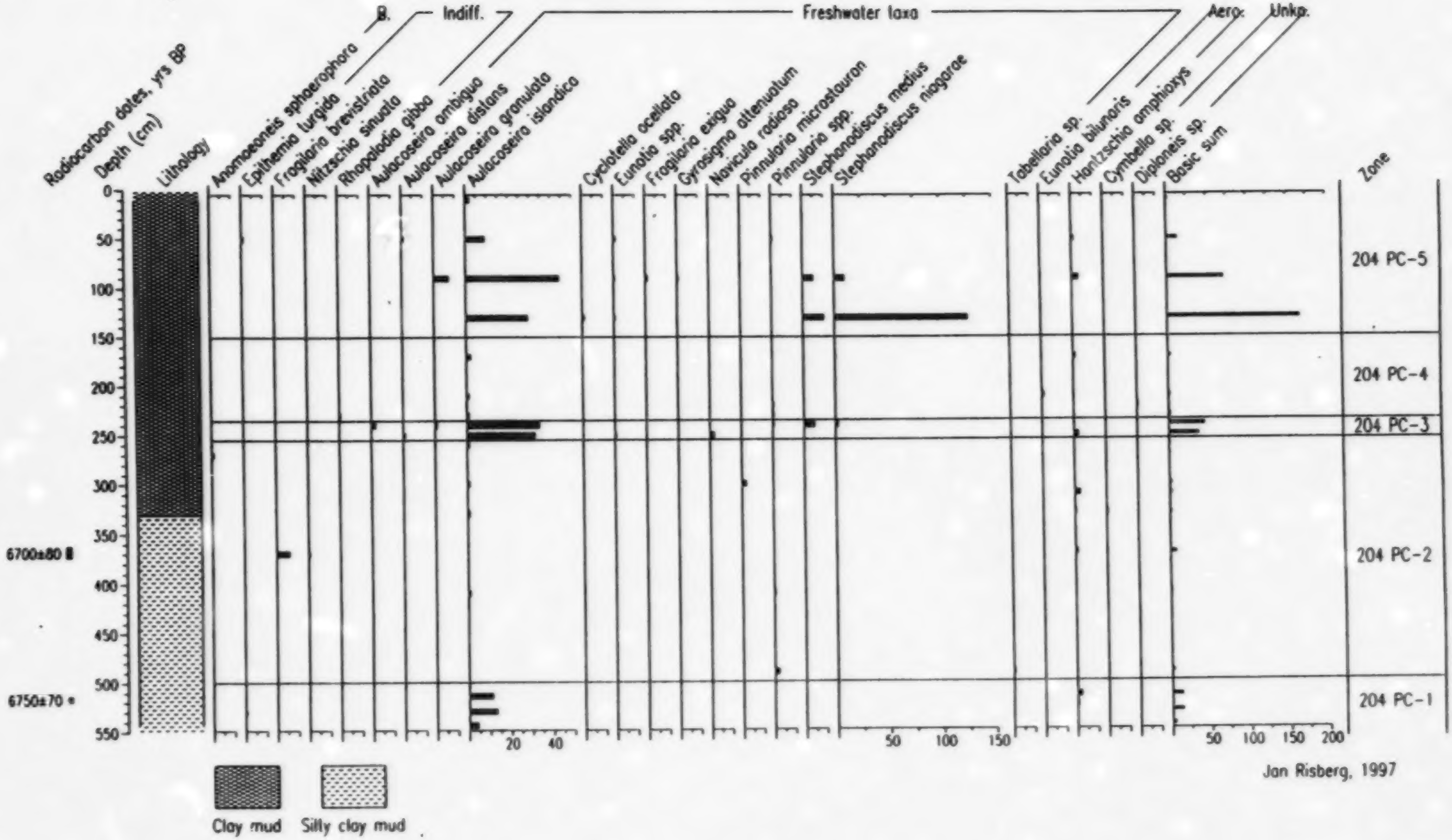
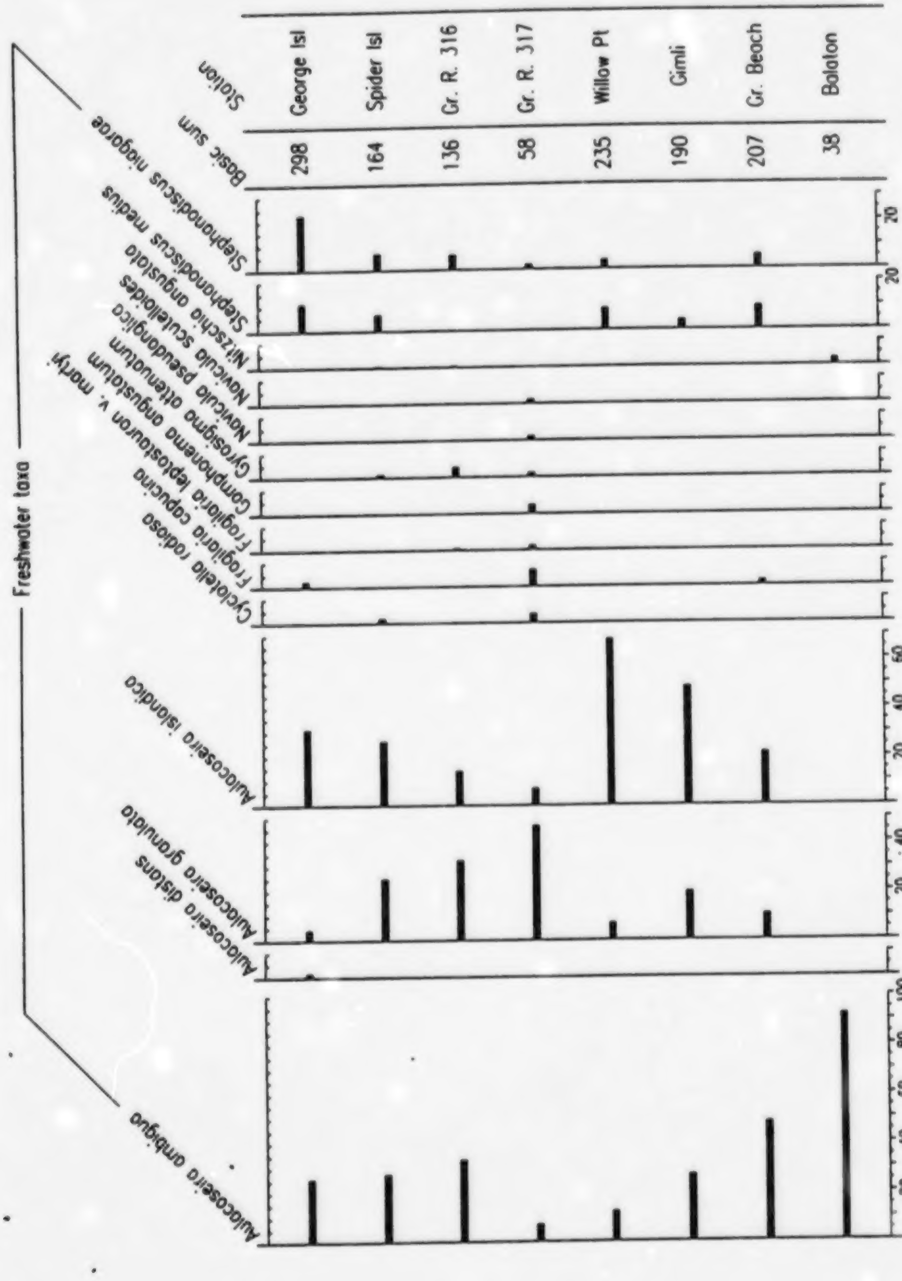

Radiocarbon dates, yrs BP
Depth (cm)
Lithology
B.
Indiff.
Freshwater taxa
Aero.
Unkn.
Anomoeoneis sphaerophora
Epithemia turgida
Fragilaria brevistriata
Nitzschia sinuata
Rhopalodia gibba
Aulacoseira ambigua
Aulacoseira distans
Aulacoseira granulata
Aulacoseira islandica
Cyclotella ocellata
Eunotia spp.
Fragilaria exigua
Gyrosigma attenuatum
Navicula radiosa
Pinnularia microstauron
Pinnularia spp.
Stephanodiscus medius
Stephanodiscus niagarae
Tabellaria sp.
Eunotia bilunaris
Hantzschia amphioxys
Cymbella sp.
Diploneis sp.
Basic sum
Zone
204 PC-5
204 PC-4
204 PC-3
204 PC-2
204 PC-1
0
50
100
150
200
250
300
350
400
450
500
550
6700±80
6750±70
20
40
50
100
150
50
100
150
200
Clay mud
Silty clay mud
Jan Risberg, 1997

Figure 7.



Jan Risberg, 1993

Figure 8.

8.2 A revision of the ostracode stratigraphy of Lake Winnipeg sediments

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ABSTRACT

Three zones are recognized for the Quaternary sediments in Lake Winnipeg on the basis of ostracode assemblages from piston cores. The oldest zone, **C**, and the lower part of the overlying zone **B** are associated with Lake Agassiz and Lake Winnipeg sediments. The upper part of zone **B** and the barren zone **A**, at the top of the sequence, are associated with Lake Winnipeg sediments. The succession of zones indicate deep-water conditions during deposition of the lower and middle parts of the Lake Agassiz sediments (zone **C**). This was followed by shallower water depths during deposition of the upper part of the Lake Agassiz sediments and the Lake Winnipeg sediments (zones **B** and **A**). At some core sites, the boundary between zones **C** and **B** is associated with an unconformity and at other sites the boundary between the zones is conformable. Accelerator mass spectrometer ages for seeds and biogenic carbonate from zone **B** range from as old as 9,170 ± 70 BP to as young as 3,870 ± 140 BP.

INTRODUCTION

Samples from piston cores collected during Cruise 96-900 of the CCGS *Namao* were processed to determine the ostracode fauna present in the deposits beneath the floor of Lake Winnipeg. Five of the piston cores are from the North Basin and the other piston core is from the South Basin (Table 1 and Fig. 1). Samples ranging in volume from 5 to 12 cc were wet-sieved in a 63 µm sieve and the residues were examined for ostracodes. A total of 228 samples was processed. An overview of the zones in the cores based on the ostracodes in the residues is presented in this report.

DESCRIPTION OF ZONES

Three zones were recognized for the piston cores collected during Cruise 94-900 of the CCGS *Namao* in Lake Winnipeg (Rodrigues, 1996). The same successions of zones have been identified in the 96-900 cores (Table 2 and Fig. 2). Ostracodes are absent or present in low numbers (*Candona subtriangulata*) in the oldest zone (**C**). Zone **B** is subdivided into a lower **B2** interval and an upper **B1** interval. The **B2** interval is characterized by *Candona rawsoni*, *C. subtriangulata* and *Limnocythere friabilis*. *Cytherissa lacustris* is present in the upper part of the **B2** interval. Fragments of ostracode valves, commonly etched and pitted, are present in the **B1** interval. Ostracodes are absent in the youngest zone (**A**).

In the 94-900 cores, zone **B** is restricted to Lake Winnipeg sediments which are unconformably underlain by Lake Agassiz sediments. This relationship is also recognized in core 206 from the 96-900 suite of cores (Fig. 2). However, in some of the 96-900 cores, the boundary between Lake Agassiz and Lake Winnipeg sediments is conformable (204 and 205, Fig. 2) and in these cores the **B2** interval extends into the upper part of the Lake Agassiz sediments. Interval **B1** is present above the Agassiz-Winnipeg boundary in all cores form the North Basin except core 207 (Fig. 2) where the upper part of the Lake Agassiz sediments are stiff and crumbly. Interval **B1** was not recognized in core 220 from the South Basin (Fig. 2).

DISCUSSION

The monospecific *Candona subtriangulata* assemblages associated with zone **C** indicate relatively deep-water conditions, up to 200 m, during deposition of the lower to middle part of the Lake Agassiz sediments. The presence of *Limnocythere friabilis* in zone **B** suggests that the water depth was shallower during deposition of the upper part of the Lake Agassiz sediments and the Lake Winnipeg sediments.

Reworked benthonic foraminiferal tests, *Cassidulina reniforme* and *Elphidium excavatum* forma *clavata*, were observed in three samples between 300 and 540 cm (interval **B2**) in core 204 from the North Basin. The origin of the marine foraminiferal tests has not been determined. Contamination from the sieve used in processing the samples does not appear likely because the samples were processed at different times and in different sieves.

Accelerator mass spectrometer ages for seeds and biogenic carbonate from the piston cores are listed in Table 3. The ages are for materials from zone **B** (Fig. 2). They range from 9,170 ± 70 to 6,700 ± 80 BP in the North Basin and from 4,760 ± 70 to 3,870 ± 140 BP in the South Basin.

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I would like to thank Brian Todd for preparing Figure 1.

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Figure 2. Successions of ostracode zones in piston cores from Lake Winnipeg.

Table 1. Water depths for cores, length of cores and samples processed.

Basin	Core Number	Water Depth (m)	Length (m)	Number of Samples Processed	Sample Interval (cm)
North	202	13.6	5.89	39	5, 15 and 20
	204	15.9	5.79	56	10
	205	15.9	5.37	70	5, 10 and 20
	206	15.9	4.96	23	20
	207	17.1	3.44	14	20
South	220	10.5	5.53	26	20 and 25

Table 2. Summary of zones in the cored sections.

Sequence	Zone		Description
Winnipeg	A		Ostracodes absent.
	B	B1	Fragments of ostracode valves; generally pitted and etched.
		B2†	*Candona rawsoni*, *C. subtriangulata* and *Limnocythere friabilis* present throughout the zone; generally in low numbers. Low numbers of *Cytherissa lacustris* are present in the Winnipeg sequence.
Agassiz	C		Ostracodes absent or present in low numbers (*Candona subtriangulata*).

† Low numbers of reworked foraminiferal tests (*Cassidulina reniforme* and *Elphidium excavatum* forma *clavata*) were observed in three samples from interval **B2** in Core 204.

Table 3. AMS ages for seeds and biogenic carbonate from zone B.

Core	Interval (cm)	Dated Material	Laboratory Number	^{14}C Age (BP)
220	395-400	*Scirpus* seed	CAMS-46193	3,870 ± 140
220	535-540	Goosefoot seeds	CAMS-35495	3,920 ± 70
220	542-547	Pelecypod valve	CAMS-32193	4,760 ± 70
204	362-373	Ostracodes	CAMS-38676	6,700 ± 80
204	513-518	Spruce needle	CAMS-38678	6,750 ± 70
202	174-179	Ostracodes	CAMS-32192	6,810 ± 60
207	155-163	Ostracodes	CAMS-38677	9,170 ± 70

The ages were determined at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory and are reported in radiocarbon years using the Libby half life of 5,568 years. Sample preparation backgrounds were subtracted, based on measurements of samples of ^{14}C free coal. Backgrounds were scaled relative to sample size.

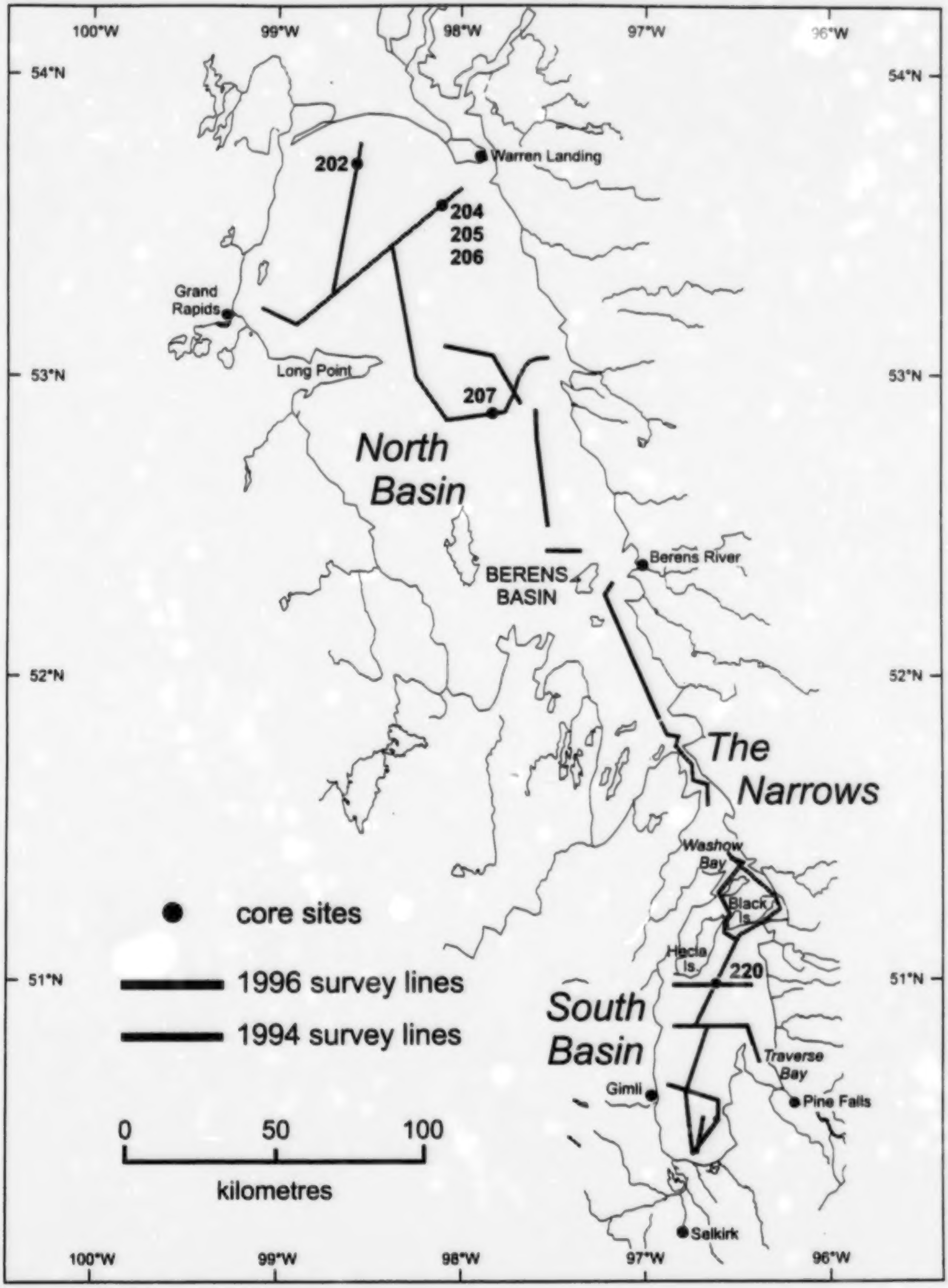
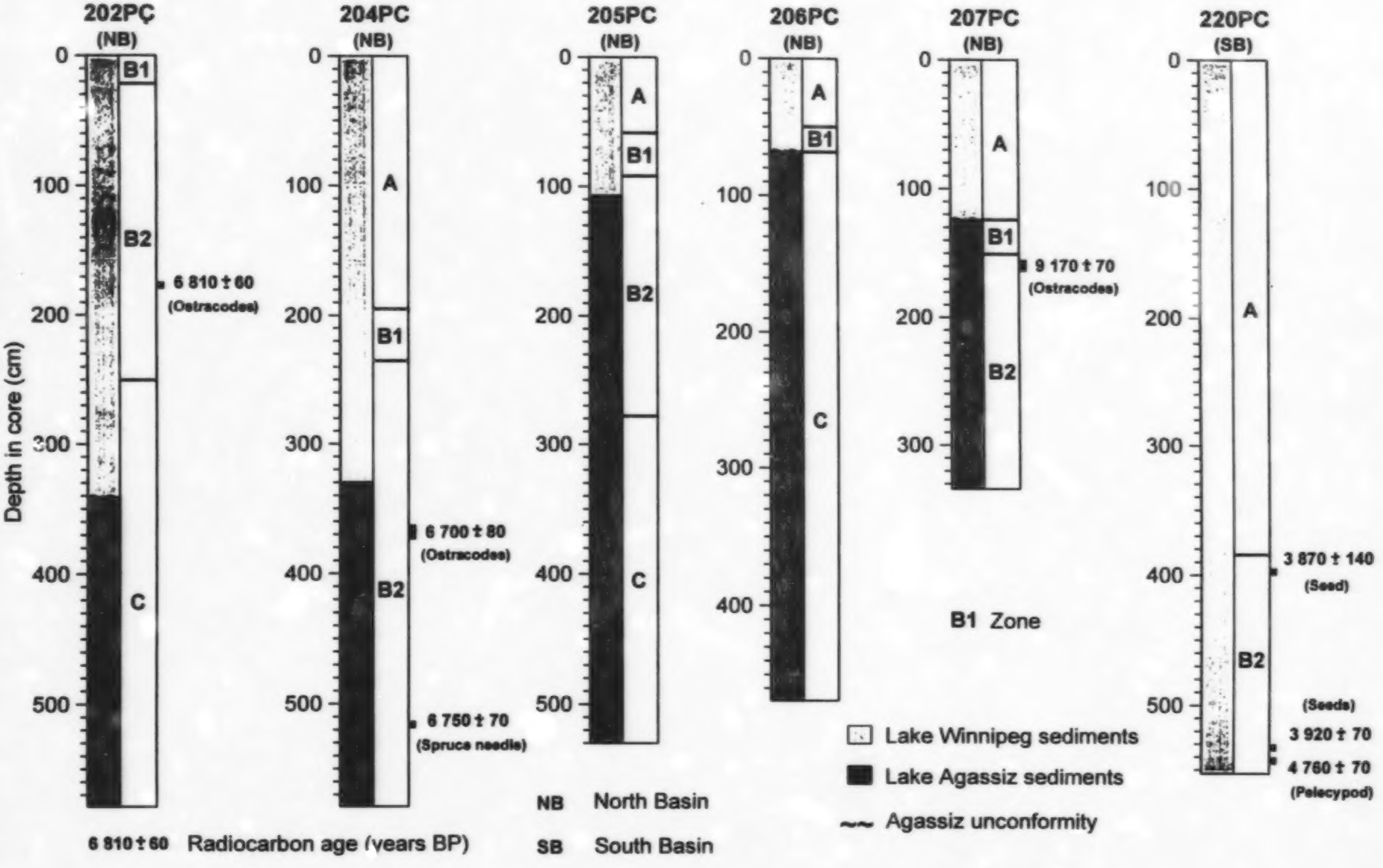

100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
202
204
205
206
207
220
Warren Landing
Grand Rapids
Long Point
North Basin
BERENS BASIN
Berens River
The Narrows
Washow Bay
Black Is.
Hecla Is.
South Basin
Traverse Bay
Gimli
Pine Falls
Selkirk
core sites
1996 survey lines
1994 survey lines
0
50
100
kilometres

Figure 1. Location of core sites.


202PÇ
(NB)
204PC
(NB)
205PC
(NB)
206PC
(NB)
207PC
(NB)
220PC
(SB)
Depth in core (cm)
0
100
200
300
400
500
A
B1
B2
C
6 810 ± 60
(Ostracodes)
6 700 ± 80
(Ostracodes)
6 750 ± 70
(Spruce needle)
9 170 ± 70
(Ostracodes)
3 870 ± 140
(Seed)
(Seeds)
3 920 ± 70
4 760 ± 70
(Pelecypod)
6 810 ± 60 Radiocarbon age (years BP)
NB North Basin
SB South Basin
B1 Zone
Lake Winnipeg sediments
Lake Agassiz sediments
~~ Agassiz unconformity

8.3 Plant and insect macrofossils in Lake Winnipeg sediments: accelerator mass spectrometry radiocarbon dating and paleoenvironmental inferences

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ABSTRACT

Macrofossils of terrestrial plants and insects were used to obtain ages for sedimentation in Lake Winnipeg and for the reconstruction of paleoenvironments primarily with respect to shoreline proximity. Basal ages for Lake Winnipeg sedimentation in the North Basin shortly postdate the drainage of Lake Agassiz at about 7 ka whereas corresponding ages in the South Basin cluster around 4 ka. Bulk sediment radiocarbon age determinations are in error by several millennia due to the influence of old carbon. Calcareous fossil ages are in error by several centuries or more. Basal Lake Winnipeg sediments especially in the South Basin, contain far more shoreline proximity indicators than do modern offshore sediments indicating expansion and deepening of the lake, continuing into late Holocene time.

INTRODUCTION

It is important for Quaternary geologists studying lacustrine environments to be able to precisely date stratigraphic sequences in relation to the information these sequences provide towards the sedimentological history and paleohydrology of a lake basin. The most valuable tool available to Quaternary geologists in providing good chronological control is the use of plant and insect macrofossils for accelerator mass spectrometry (AMS) dating. Compared to conventional radiocarbon dating, the AMS ^{14}C technique has the advantage of dating small samples (minimum 0.5 mg) with high accuracy. This advantage, combined with the ability of a Quaternary macrofossil specialist to examine lacustrine sediments for well defined macrofossils suitable for AMS dating, problems such as 'hard-water' effects and reworking of older sediments can be avoided. Macrofossils not only provide a means of obtaining good chronological control but also provide paleoecological information on the depositional environment, which can be used effectively in reconstructions of past local environments.

Lake Winnipeg, the eleventh largest freshwater lake in the world, has a surface area over 25% larger than Lake Ontario (Todd et al., 1998). Despite its immense size and importance in providing Manitoba's economy with hydroelectric generation, recreation and fisheries, it has not been the subject of geological investigations until recently. In order to better understand the geological history of Lake Winnipeg and address concerns regarding shoreline erosion, a geophysical, geological and limnological research program was initiated in 1994 (Todd et al., 1996). This activity included collection of a series of lake sediment cores in both 1994 (Lewis and Todd, 1996) and in 1996 (Lewis et al., this volume).

Previous knowledge of the Quaternary geochronology of Lake Winnipeg has been limited to a few studies on shoreline features and sites adjacent to Lake Winnipeg. Stewart (reported in Penner and Swedlo, 1974) dated peat from below lake level at Elk Island, providing evidence of lake level rise of 3 m over the past 1.7 ka. Ritchie and Hadden (1975) dated bulk sediment from a shallow lake on The Pas moraine, the large peninsula in the North Basin, providing a minimal age of 7.2 ka for the recession of Glacial Lake Agassiz. Hence, the geochronology of Lake Winnipeg was virtually unknown at the outset of recent investigations. Therefore, obtaining reliable age determinations on major stratigraphic features within Lake Winnipeg sediments became a key priority for the project. Radiocarbon dating of bulk sediment conducted by Lewis and Todd (1996) yielded age estimates several thousand years older than a corresponding macrofossil age determination obtained by Vance and Telka (1998), indicating contamination likely derived from carbonaceous rocks in the drainage basin (Nambudiri et al., 1980). Although no evidence of reworked coal or amber were observed in the sediments, Anderson (personal communication) reports the existence of at least 10% pre-Quaternary palynomorphs within Lake Winnipeg South Basin sediments. The project therefore shifted to exclusive reliance on dating of well preserved macrofossils of taxa reliant on atmospheric carbon. In addition to a radiocarbon chronology, macrofossil analyses have also provided crucial data for paleoenvironmental reconstruction.

METHODS

Three groups of subsamples were obtained from the 1996 cores for radiocarbon dating and paleoenvironmental analysis. Eleven top-of-core samples from the 1996 cores were examined to obtain information regarding the modern floral and faunal assemblages. A complete profile was taken at site 223. Thirdly, a major effort was made to obtain basal ages of Lake Winnipeg sedimentation.

Macrofossils within Lake Winnipeg cores were extracted by gentle sieving of approximately 90 ml of wet sediment using tap water and nested sieves with the smallest mesh opening being 250 microns (0.25 mm). Plant and insect macrofossils, consisting mostly of seeds, fruits and insect fragments were identified with the aid of a stereomicroscope using various illustrations and taxonomic keys and verified by comparisons to the modern reference collections of vascular plant remains and insects housed at the Geological Survey of Canada in Ottawa. In addition to comparison of the fossil remains to modern reference material, eleven top-of-core sediment samples from Lake Winnipeg cores collected in 1996 were also examined.

To eliminate any sources of contamination from biological growth, macrofossils suitable for AMS dating were immediately air dried, weighed, photographed and stored dry in pre-rinsed, sterilized (heated to 105°C) glass vials prior to submission for dating. Wohlfarth et al. (1998) have found that long-term storage of wet macrofossil samples, even when stored at cool temperatures (5°C) in slightly acidic (10% HCl) distilled water can lead to anomalously younger ages especially if no pretreatment was performed in the AMS laboratory. AMS ages were obtained at the Lawrence Livermore National Laboratory, Center for Accelerator Mass Spectrometry, University of California. Pretreatment for all AMS samples included standard acid-base-acid washes in 1N HCl and 1N NaOH.

RADIOCARBON SELECTION CRITERIA

Material was selected for radiocarbon analysis to minimize incorporation of reworked material, and to isolate taxa that obtain carbon from the atmosphere. Degree of reworking was assessed on the basis of the range of habitats represented by the fossil assemblage, as well as on the basis of signs of wear. Where a mixture of fossils from different plant communities/habitats (such as emergent, shoreline and upland) was observed, those from either the emergent assemblage, or the dominant assemblage were favoured. The reason for this criterion is the assumption that fossils derived from a habitat significantly different from the dominant assemblage are more likely to have been reworked from a deposit that could be much older than the sediments or core level to be dated. Although none of the plant macrofossil assemblages within Lake Winnipeg sediments represent *in situ* deposits, those displaying minimal signs of wear were assumed to have been deposited close to the source, i.e., minimal transition from terrestrial environments to offshore sedimentation. Fossils selected for ^{14}C analysis were described with respect to their degree of preservation as excellent, good, fair, or poor. Those described as excellent (Table 1) bear delicate features such as intact, fragile ornamentation. Those described as good retain some of their vulnerable surface features, while those judged to be fair retain only traces of these features. Those described as poor have lost surface features apparently through mechanical abrasion.

Lake Winnipeg basin sediments and waters are likely to contain pre-Quaternary carbon derived both from underlying Paleozoic carbonates as well as from carbonaceous Mesozoic shales that occur to the west. Glacial and fluvial sediments in the basin are rich in debris derived from these rocks (Nielsen and Thorleifson, 1996), hence these rocks are likely an important source for carbonate and other forms of carbon observed in Lake Winnipeg sediments (Henderson and Last, 1998). Thus for radiocarbon dating, an effort was made to select fossil remains that are more likely to be contemporaneous with deposition. To avoid the problem of derivation of carbon from dissolved carbon dioxide or bicarbonate from within the watershed, only taxa that obtain their carbon supply from the atmosphere, such as terrestrial or emergent plants, or terrestrial insects were used. This means that despite their abundance, remains of submergent plant species such as pondweeds (*Potamogeton* sp.) were avoided.

RESULTS

A total of 39 AMS and conventional radiocarbon dates were obtained from Lake Winnipeg 1994 and 1996 offshore cores. Telka (this volume) has compiled detailed information regarding each age determination as an appendix. In addition to reporting on offshore radiocarbon dates, the appendix also includes 10 dates from coastal features obtained by Forbes (in prep.) and 36 dates on materials collected in the shoreface and marshes (Nielsen, this volume).

Conventional and AMS dating of six bulk sediment samples from core 122a in the South Basin yielded ages ranging from 4.0 to 11.0 ka (Table 1, CAMS-19445 to19449, BETA-81335) (Lewis and Todd, 1996, Table 1). These ages were in conflict with an AMS result on one well preserved bulrush (*Scirpus* sp.) seed from the same core (Table 1, CAMS-17434; Vance and Telka, 1998). This exceptionally well preserved seed from peat directly overlying Lake Agassiz clayey silt yielded an AMS date of 4.0 ka. In comparison, AMS date on bulk sediment of weakly calcareous clay-silt mud 37 cm above the dated peat section yielded an age of 11.0 ka (Table 1, BETA-81335). This discrepancy is attributed to allochthonous carbon bearing rocks within Lake Winnipeg sediments.

The first attempt to obtain more reliable age determinations from Lake Winnipeg sediments met with limited success. A total of 64 subsamples from eleven cores collected in 1994 were processed, but only 4 AMS dates, two on twigs and the remaining two on ostracodes were obtained from the scarce materials recovered.

Using the 1996 Lake Winnipeg cores, a more comprehensive attempt at isolating terrestrial macrofossils for dating was carried out with more cores and larger number of samples being examined. From 21 cores and 110 samples analyzed, 28 AMS age determinations were obtained including 22 dates on terrestrial macrofossils and 3 each on ostracodes and molluscs.

Despite the recovery of hundreds of recognizable fossil remains in many samples, few of the samples fulfilled the ideal selection criteria with respect to degree of preservation. This is probably attributable to wave action during the transition from terrestrial environments to offshore sedimentation.

North Basin sediments contain far fewer macrofossils than those of the South Basin (Tables 2 and 3). Presumably this is due to the greater distance of the sites offshore, the possible lack of early Holocene subaerial exposures (Lewis and Todd, 1996), steeper offshore gradients and hence less extensive emergent vegetation, and perhaps due to lower aquatic productivity at that latitude.

The following observations may be made regarding radiocarbon age determinations from Lake Winnipeg:

Bulk sediment ages are rejected based on the assumption that they are likely to contain rebedded carbon due to the presence of carbonaceous rocks and sediments in the basin. Bulk sediment radiocarbon dates have yielded age estimates several thousand years older than corresponding macrofossil AMS dates.

Basal Lake Winnipeg ages in the North Basin approach 7 ka, whereas equivalent South Basin results cluster around 4 ka, indicating a delay in the initiation of South Basin sedimentation.

Ostracode carbonate from site 204 yielded an age similar to that obtained from terrestrial organic remains over 1.5 m deeper in the core (Table 1, CAMS-38767 and CAMS-38678, 6.7 ka). An old-carbon effect is suspected as the cause of this anomaly. Similarly, seeds and shell dated from the same interval from site 220 imply a roughly 0.8 ka offset in apparent age (Table 1, CAMS-35495 and CAMS-32193). Similar findings by Andree et al. (1986) on AMS dated gyttja and carbonates also reveal apparent ages 0.8 ka older than dates on terrestrial material. Nielsen et al. (1982) reported an apparent age of about 400 years for a modern shell collected prior to atmospheric nuclear weapons testing.

Although an old carbon problem was suspected in the case of submerged aquatics, no comparisons were obtained to test this possibility. Dates from the same interval obtained on aquatic emergent and upland taxa from site 224 compare favorably with an age difference of only 20 ± 50 years (Table 1, CAMS-35501 and CAMS-35496) allaying any suspicions that aquatic emergent plants draw some of their carbon from the basin reservoir.

PALEOENVIRONMENTAL ANALYSIS

The principle paleoenvironmental inference that may be made from the macrofossil assemblages is shoreline proximity, judged on the basis of presence and abundance of the remains of shoreline and marsh-dwelling taxa. Modern sediments at offshore sites contain few such indicators if any. In contrast, basal Lake Winnipeg sediments, especially in the South Basin, contain abundant shoreline proximity indicators.

Site 223, South Basin

29 sediment samples, each amounting to 45-90 ml of wet sediment from core 223 (Figure 1) were analyzed for macrofossil content for the purpose of paleoenvironmental reconstruction. Sampling density varied, with more samples

being examined within the basal portion of the core (spanning every 10 cm) compared to the upper 5 m (spanning every 50 cm). Core 223 is divided into 5 zones (Figure 2) based upon floral composition and density of shoreline indicators.

Zone 5 (739-721 cm)

Only a few fragments of molluscs and ostracode valves and single seeds of poorly preserved spike-rush (*Eleocharis* sp.) and goosefoot (*Chenopodium* sp.) occur near the base of calcareous organic silty clay unit of zone 5, suggesting relatively deep water conditions during deposition. The firm, crumbly consistency of the clay within this zone is characteristic of Lake Agassiz type sediments which typically contain no organics. However, near the top of zone 5, small concentrations of organics in 'ball form' appear within the clay. A date of 4 ka (Table 1, CAMS-46186) on one bulrush seed (*Scirpus* sp.) from the concentrated organics provides an age estimate for the beginning of Lake Winnipeg sedimentation in the South Basin. The organics represent reworked material which have been incorporated into Lake Agassiz sediments possibly caused by drainage and/or wave action in the basin.

Zone 4 (721-677.5 cm)

Unique to zone 4 are two layers of organics, one deposited near the base of organic silty clay (700-704 cm) the second, a silty peat layer (677.5-687 cm). As such, zone 4 is characterized by its abundance and diversity of plant macrofossils. Overall, grasses (Gramineae), composits (Compositae), coast-blite (*Chenopodium rubrum* type), dock (*Rumex* sp.), spike rush (*Eleocharis* spp.), horned pondweed (*Zannichellia palustris*) and skunkweed (*Chara/Nitella*) dominate the plant macrofossil assemblages within this zone.

The organic rich layer near the base of zone 4 (700-704 cm) comprises mostly seeds of coast blite (*Chenopodium rubrum*), grasses (Gramineae) and dock (*Rumex* sp.) with minimal representation of aquatic taxa. This suggests a decline in water level at site 223 in comparison to zone 5. Above this organic rich layer there is a steady increase in horned pondweed (*Zannichellia palustrus*), spike rush (*Eleocharis acicularis*) and a few Northern Seaside buttercup (*Ranunculus Cymbalaria*) plants which thrive in saline conditions. The combined evidence suggests a shallow, exposed shoreline at site 223 nearing an evaporative phase throughout the remaining portion of zone 4.

Zone 3 (677.5-550 cm)

Zone 3 from silty clay mud contains many of the same plant taxa encountered in the lower organic rich zone 4 but their numbers decline dramatically. An age determination of 4.0 ka (Table 1, CAMS-34551) on dated bulrush (*Scirpus* sp.) seed 10 cm above sharp contact (677.5 cm) at the base of zone 3 implies rapid sedimentation between zone 5 and 3. 30 radiocarbon years separate zone 5 (Table 1, CAMS-46186) and zone 3. The decrease in numbers of shoreline proximity indicators throughout zone 3 is an indication of a rise in lake level in the South Basin.

Zone 2 (550-500 cm)

The silty clay mud of zone 2 suggests relatively stable water conditions, although the macrofossils indicate the onset of marsh conditions. Cat-tail (*Typha* sp.) and bulrushes (*Scirpus* sp.) dominate the assemblage. A date of 3.3 ka on one well preserved bulrush seed from near the top of zone 2 (Table 1, CAMS-34550) provides an age estimate for the onset of marsh conditions at site 223.

Zone 1 (500-surface)

Shoreline macrofossil indicators are well represented in the basal portion of core 223 (zone 4 and 2), compared to zone 1. Plant macrofossils diminish in numbers in the upper 5 m of clay mud suggesting shoreline was moving away from the site and that Lake Winnipeg in the South Basin has been expanding since 3.3 ka.

CONCLUSIONS

Reliable age determinations for the initiation and progress of Lake Winnipeg sedimentation may be obtained from the majority of core intervals by screening several tens of ml of sediment at 0.25 mm, and by searching for and isolating well preserved fossils of taxa that derive their carbon from the atmosphere. In contrast, bulk sediment dates may be several thousand years older than the time of deposition; while calcareous fossils often provide results centuries to millennia in error.

Basal Lake Winnipeg sedimentation in the North Basin dates to the early Holocene, whereas corresponding age determinations for the South Basin cluster around 4.0 ka.

Basal Lake Winnipeg sediments, especially in the South Basin, contain abundant shoreline taxa indicating proximity to shoreline. Fossils (or lack of them) from overlying sediments suggests more distal shoreline positions and deepening water.

Paleoenvironmental analysis and AMS dating of plant and insect macrofossils from Lake Winnipeg sediments have provided significant information on the sedimentological history and paleohydrology of the lake basin. Accurate dating results on sedimentological sequences can only be obtained by careful examination and selection of well defined macrofossils suitable for AMS dating. This, combined with the advantages of using small sample size (i.e. one macrofossil seed) for AMS dating, problems such as 'hard-water' effects of dating bulk sediments suspected of containing old carbon can be avoided.

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TABLE 1. Lake Winnipeg Offshore C14 Radiocarbon Dates

Site/Sample Number	Lab Number	Age (yrs BP)	Taxon	Material Type	Preservation	Age Significance
94900 LW 104aGC 237-243 cm	CAMS-32189	7700 ± 50	twigs	upland	fair	Lake Winnipeg (non basal)
94900 LW 106PC 176-182 cm	CAMS-32191	6910 ± 200	ostracodes	carbonate	na	Lake Winnipeg (basal)
94900 LW 106PC 174-179 cm	CAMS-38675	6900 ± 80	ostracodes	carbonate	na	Lake Winnipeg (basal)
94900 LW 115PC 256-263 cm	CAMS-32190	3060 ± 70	twig	upland	good	Pearson Reef paleobeach, shoreface
94900 LW 122aGC 425-433 cm	CAMS-17434	4040 ± 70	*Scirpus* sp. seed	aquatic emergent	excellent	Lake Winnipeg (basal)
94900 LW 122aGC 17-23 cm	CAMS-19445	3990 ± 50	bulk sediment	lake sediment	na	Lake Winnipeg (non basal)
94900 LW 122aGC 118-123 cm	CAMS-19446	5820 ± 50	bulk sediment	lake sediment	na	Lake Winnipeg (non basal)
94900 LW 122aGC 188-192 cm	CAMS-19447	6900 ± 60	bulk sediment	lake sediment	na	Lake Winnipeg (non basal)
94900 LW 122aGC 268.5-272 cm	CAMS-19448	7570 ± 50	bulk sediment	lake sediment	na	Lake Winnipeg (non basal)
94900 LW 122aGC 318.5-322 cm	CAMS-19449	7560 ± 70	bulk sediment	lake sediment	na	Lake Winnipeg (non basal)
94900 LW 122aGC 388.5-392 cm	BETA-81335	11050 ± 270	bulk sediment	lake sediment	na	Lake Winnipeg (non basal)
96900 LW 201PC 434-439	CAMS-35499	4800 ± 70	*Picea* sp. needles	upland	poor	Lake Winnipeg (basal)
96900 LW 202PC 174-179 cm	CAMS-32192	6870 ±60	ostracodes	carbonate	na	Lake Winnipeg (basal?)
96900 LW 204PC 362-373 cm	CAMS-38676	6700 ± 80	ostracodes	carbonate	na	Lake Winnipeg (non basal)
96900 LW 204PC 513-518 cm	CAMS-38678	6750 ± 70	*Picea* sp. needles	upland	poor	Lake Winnipeg (non basal)
96900 LW 207PC 155-163 cm	CAMS-38677	9170 ± 70	ostracodes	carbonate	na	Lake Agassiz
96900 LW 209PC 95-97cm	CAMS-35497	3730 ± 70	*Juniperus communis* L. seed	upland	excellent	Lake Winnipeg (basal)
96900 LW 213PC 10-15 cm	CAMS-46187	2540 ± 60	*Picea* sp. needle	upland	poor	Lake Winnipeg (basal)
96900 LW 214PC 298-303 cm	CAMS-38679	3630 ± 50	wood	upland	fair	Lake Winnipeg (non basal)
96900 LW 215PC 321.5 cm	CAMS-34554	3950 ± 60	*Scirpus* sp. seed	aquatic emergent	fair	Lake Winnipeg (non basal)
96900 LW 215PC 348 cm	CAMS-34555	4030 ± 50	*Scirpus* sp. seed	aquatic emergent	good	Lake Winnipeg (non basal)
96900 LW 217PC 127-132 cm	CAMS-35498	3340 ± 50	*Scirpus* sp. seed	aquatic emergent	excellent	Lake Winnipeg (non basal)
96900 LW 217PC 135-140 cm	CAMS-46190	3340 ± 40	*Scirpus* sp. seeds	aquatic emergent	good	Lake Winnipeg (non basal)
96900 LW 217PC 253-257 cm	CAMS-46191	3910 ± 60	*Chenopodium* sp. seeds	shoreline	excellent	Lake Winnipeg (non basal)
96900 LW 219PC 372-377 cm	CAMS-35494	1970 ± 170	terrestrial insect parts	shoreline	excellent	Pearson Reef paleobeach, lagoon
96900 LW 219PC 436-439 cm	CAMS-35500	2940 ± 80	*Rubus idaeus* L. seeds	shoreline	poor	Pearson Reef paleobeach, lagoon
96900 LW 220PC 395-400 cm	CAMS-46193	3870 ± 140	*Polygonum amphibium* L. seed	aquatic emergent	excellent	Pearson Reef paleobeach, shoreface
96900 LW 220PC 535-540 cm	CAMS-35495	3920 ± 70	*Chenopodium* sp. seeds	shoreline	excellent	Pearson Reef paleobeach, shoreface
96900 LW 220PC 542-547 cm	CAMS-32193	4760 ± 70	shell	carbonate	na	Pearson Reef paleobeach, shoreface
96900 LW 221PC 523-528 cm	CAMS-38680	4190 ± 100	*Scirpus* sp. seed	aquatic emergent	fair	Lake Winnipeg (basal)
96900 LW 221PC 526-527 cm	CAMS-35616	4320 ± 50	*Sphaerium striatinum* shell	carbonate	excellent	Lake Winnipeg (basal)
96900 LW 222PC 735-740 cm	CAMS-46188	4710 ± 50	*Scirpus* sp. seed	aquatic emergent	fair	Lake Winnipeg (basal)
96900 LW 223PC 507-509 cm	CAMS-34550	3280 ± 60	*Scirpus* sp. seed	aquatic emergent	excellent	Lake Winnipeg (non basal)
96900 LW 223PC 661-666 cm	CAMS-34551	4000 ± 60	*Scirpus* sp. seed	aquatic emergent	fair	Lake Winnipeg (non basal)
96900 LW 223PC 721-726 cm	CAMS-46186	4030 ± 50	*Scirpus* sp. seed	aquatic emergent	good	Lake Winnipeg (basal)
96900 LW 224PC 577-582 cm	CAMS-35496	3550 ± 70	*Helianthus* sp. seed	shoreline	excellent	Lake Winnipeg (non basal)
96900 LW 224PC 577-582 cm	CAMS-35501	3570 ± 120	*Scirpus* sp. seeds	aquatic emergent	good	Lake Winnipeg (non basal)
96900 LW 224PC 584-589 cm	CAMS-46192	5350 ± 50	*Scirpus* sp. seed	aquatic emergent	poor	Lake Winnipeg (non basal)
96900 LW 224PC 705-710 cm	CAMS-35615	4090± 60	shell	carbonate	good	Lake Winnipeg (non basal)

TABLE 2. Lake Winnipeg Floral Macrofossils associated with AMS dated terrestrial samples

Taxa		North Basin Cores					South Basin Cores															
		201 (434-439)	204 (513-518)	209 (95-97)	213 (10-15)	214 (298-303)	215 (321.5)	215 (348)	217 (127-132)	217 (135-140)	217 (253-257)	219 (372-377)	219 (436-439)	220 (395-400)	220 (535-540)	221 (523-528)	222 (735-740)	223 (507-509)	223 (661-666)	223 (721-726)	224 (577-582)	224 (584-589)
Characeae																						
Chara/Nitella type	a			+			+											+	+	++	+	+
Bryophytes ...."mosses"	a/s		+		+	+	+		+		+		+	+				+			+	+
Sphagnum sp.	a/s			+	+	+												+			+	+
Sparganiaceae ....."bur reed family"																						
Sparganium sp.	ae										+										+	
Typhaceae........."Cat-tail family"																						
Typha sp.	ae	+	+	++	+	+	+	+	+		+	+					+	++	+		+	+
Potamogetonaceae .."pondweed family"																						
Potamogeton sp.	a						+	+	+		+							+				
Zanichellia palustris L.	a																+					+
Najadaceae.... ...."Naid family"																						
Najas flexilis (Willd.)	a							+			+								+			
Alismaceae ......"water plantain family"																						
Sagittaria sp.	ae						+	+	+	+								+		+	+	+
Cyperaceae ...."sedge family"																						
Carex lenticular type	ae								+		+							+				
Carex sp.	ae							+	+	+									+	+		
Carex trigonous type	ae						+				+							+				+
Eleocharis sp.	ae						+	+										+	+	+		
Scirpus sp.	ae						+	++	+	+	+		+	+	+	+	+	+++	+	+	+	+
Polygonaceae ......"buckwheat family"																						
Polygonum amphibium L.	ae													+							+	
Callitrichaceae ..."water-starwort family"																						
Callitriche sp.	a										+											
Gramineae ...."grass family"	s						+	+		+								+	+	+	+	
Juncaceae ...."rush family"																						
Juncus/Luzula type	s																	+	+			
Polygonaceae ......"buckwheat family"																						
Polygonum lapathifolium L.	s						+	+	+		+							+			+	+
Polygonum sp.	s													+					+		+	
Rumex sp.	s						+	+	+	+	+		+	+			+	+	+	+	+	+
Chenopodiaceae ...."goosefoot family"																						
Chenopodium sp.	s						+		+	+	++	+	+	+	+		+	+	+	+	+	+
Salicornia rubra A. Nels.	s																				+	
Caryophyllaceae ..."pink family"	s																				+	
Ranunculaceae ....."crowfoot family"																						
Ranunculus scleratus L.	s						+		+													
Rosaceae ...."rose family"																						
Potentilla norvegica L.	s																		+			
Potentilla paradoxa Nutt.	s								+		+		++					+	+			
Potentilla sp.	s						+	+	+	+	+		+					+	+	+	+	
Rubus idaeus L.	s												+									
Prunus sp.	s														+							
Onagraceae ...."Evening primrose family"																						
Epilobium sp.	s						+		+													
Umbelliferae ......"parsley family"																						
Sium suave Walt.	s																	+				
Verbenaceae ...."vervain family"																						
Verbena sp.	s								+	+	+											
Labiatae ...."mint family"																						
Lycopus sp.	s						+		+		+											+
Mentha sp.	s						+		+													+
Plantaginaceae ...."plantain family"																						
Plantago major L.	s								+		+											
Compositae	s									+	+							+	+			
Helianthus sp.	s																	+	+		+	
Eupatorium sp.	s						+															
Pinaceae ...."pine family"																						
Picea sp	t	+	+	+	+																	
Cupressaceae ......"cypress family																						
Juniperus communis L.	t			+																		
Salicaceae ...."willow family"																						
Salix sp.	t											+										+
Betulaceae ...."birch family"																						
Betula arboreal type	t				+																	
Unidentified plant taxa				+	+		+		+	+	+		+					+	+	+	+	

Key: a=aquatic; ae=aquatic emergent; s=shoreline; a/s=includes both aquatic and shoreline taxa; t=shrub or tree; +=taxon present; +++ taxon abundant

TABLE 3. Lake Winnipeg Faunal Macrofossils associated with AMS dated terrestrial samples

Taxa		North Basin Cores					South Basin Cores															
		201 (434-439)	204 (513-518)	209 (95-97)	213 (10-15)	214 (298-303)	215 (321.5)	215 (348)	217 (127-132)	217 (135-140)	217 (253-257)	219 (372-377)	219 (436-439)	220 (386-400)	220 (535-540)	221 (523-528)	222 (735-740)	223 (507-509)	223 (661-666)	223 (721-726)	224 (577-582)	224 (584-589)
PORIFERA ...."sponges"																						
HAPLOSCLERINA																						
Spongillidae																						
Spongilla type	a	+					+	+	+	+	+	++	+	+							+	
BRYOZOA																						
Cristatella mucedo L.	a		+					+	+		+							+		+		
Plumatella sp.	a						+		+		+					+			+			
ARTHROPODA																						
INSECTA																						
EPHEMEROPTERA ...."mayflies"	a			+	+	+	+	+	+	+	+	+	+	+		+		+	+		+	+
HEMIPTERA ...."bugs"	a			+					+	+				+				+				
Corixidae ...."water boatmen"	a			+	?	+					+			+				+	+		+	
Gerridae ...."water striders"																						
Gerris sp.	a												+									
COLEOPTERA ...."beetles"																						
Dytiscidae ...."predaceous diving beetles"	a						+				+	+	+	+				+				+
Colymbetes sp.	a			+																		
Gyrinidae ...."whirligig beetles"	a																	+		+		
Hydrophilidae ....."water scavenger beetles"	a			+		+					+	+	+	+			+	+			+	
Helophorus sp.	a/s																					
Helophorus tuberculatus Gyll.	a/s			+																		
Chrysomelidae ....."leaf beetles"																						
Donacia sp.	a/s						+					+										
TRICHOPTERA ...."caddisflies"	a	+					+		+		+	+	+	+				+			+	+
DIPTERA ...."flies"																						
Chironomidae ......"midges"	a	+	+	++	+	+	+	+	+	+	+	+		+	+	+		+	+	+	+	+
CRUSTACEA																						
Cladocera ...."water fleas"																						
Daphnia sp.	a	+	+	++	+	+	+	+	+	+	+	+		+		+	+	+	+	+	+	
Notostraca ...."tadpole shrimp"																						
Lepidurus sp.	a																	+				
Ostracoda ...."ostracodes"	a	+	+				+	+	+	+	+	+		+	+	+	+	+++	++	+	++	+
ARACHNIDA																						
Acari/Oribatei...."mites, ticks, oribatid mites"	a/s									+	+			+	+							
Araneae ...."spiders"	a/s	+		+		+						+	+	+				+	+	+		
MOLLUSCA																						
Gastropoda ...."snails, limpets"	a	+					+	+++			+	+			+	+	+	+++	+	+	+++	+++
Pelecypoda ...."clams, mussels"	a	+					++	+++			+				+	+	+	++	+		++	++
ARTHROPODA																						
INSECTA																						
HEMIPTERA ...."bugs"																						
Saldidae ...."shore bugs"	s			+																		
Saldula sp.	s			+								+										
HOMOPTERA..."cicadas, hoppers, aphids etc."	s																					
Cicadellidae ...."leafhoppers"	s			+			+		?			+		+				+		+		?
Psyllidae ...."jumping plant lice"	s			+																		
COLEOPTERA ...."beetles"	s		+	+		+	+	+	+	+	+	+	+	+			+	+	+	+		
Carabidae ...."ground beetles"	s			+								+						+	+			
Apristus sp.	s											?	+									
Dyschiroides	s			+																		
Bembidion sp.	s		+	+							+	+	+					+			+	
Tachys sp.	s			+																		
Agonum sp.	s			+								+	+					+				
Amara sp.	s											+										
Selenophorus sp.	s											?										
Cercyon sp.	s			+									+									
Hydraenidae ...."minute moss beetles"	s			+																		
Ochthebius sp.	s		+	+									+	+				+			+	
Staphylinidae ....."rove beetles"	s		+	+		+			+			+	+	+				+				+
Blediini	s			+																		
Omaliinae	s			+		+																
Olophrum sp.	s			+								+										
Olophrum rotundicolle (Sahlb.)	s																	+				
Olophrum consimile Gyll.	s			+																		

Key: a=aquatic; s=shoreline/hygrophilic; a/s=includes both aquatic and shoreline taxa; f=forest; +=taxon present; +++ taxon abundant

TABLE 3. (cont'd) Lake Winnipeg Faunal Macrofossils associated with AMS dated terrestrial samples

Taxa		North Basin Cores					South Basin Cores															
		201 (434-439)	204 (513-518)	209 (96-97)	213 (10-15)	214 (298-303)	215 (321.5)	215 (348)	217 (127-132)	217 (135-140)	217 (253-257)	219 (372-377)	219 (436-439)	220 (395-400)	220 (535-540)	221 (523-528)	222 (735-740)	223 (507-509)	223 (661-666)	223 (721-726)	224 (577-582)	224 (584-589)
Stenus sp.	s			+								+						+				
Lathrobium type	s			+								+		+								
Quediini	s			+								+	+	+				+				
Quedius sp.	s																					
Aleocharinae	s	+	+	+					+	+				+				+	+			
Leiodidae ...."round fungus beetles"	s			+									+									
Ptiliidae ...."feather-winged beetles"	s																			+		
Acrotrichus sp.	s																			+		
Scaphiidae ...."shining fungus beetles"	s												+									
Histeridae ...."hister beetles"	s											+										
Scarabaeidae ......"scarab beetles"	s											+										
Aphodius sp.	s											+										
Helodidae ...."marsh beetles"	s	+	+	++		+		+				+	+	+				+	+			
Cyphon sp.	s												+									
Byrrhidae ...."pill beetles"	s																	+				
Byrrhus sp.	s											+										
Elateridae ...."click beetles"	s											+										
Lathridiidae .."minute brown scavenger beetles"	s	+		+								+		+						+	+	
Chrysomelidae ....."leaf beetles"	s			+	?		+					+		+				+				+
Gonioctena type	s			+							+											
Alticinae....."flea beetles"	s										+	+										
Curculionidae ....."weevils"	s			+			+					+	+					+		+		
Apion sp.	s						+															
Rhynchaenus sp.	s																					
Ceutorhynchus sp.	s												+					+				
Hypera sp.	s											+										
DIPTERA ...."flies"	s		+	+		+	+	+	+	+	+		+	+				+	+	+	+	+
Tipulidae ...."crane flies"																						
Tipula sp.	s										+											
HYMENOPTERA ...."wasps and ants"	s			+	+	+							+					+				+
Ichneumonoidea	s		+				+				+			+				+			+	
Formicidae	s												+								+	+
Formica type	s											+										
Scolytidae ...."bark beetles"	f			+																		
Unidentifiable animal taxa		+	+	+	+								+	+	+			+			+	+
bone	a/s	+		+		+			+		+	+	+		+		+	+	+		+	+
fish scale	a						+											+	+		+	+

Key: a=aquatic; s=shoreline/hygrophilic; a/s=includes both aquatic and shoreline taxa; f=forest; +=taxon present; +++ taxon abundant

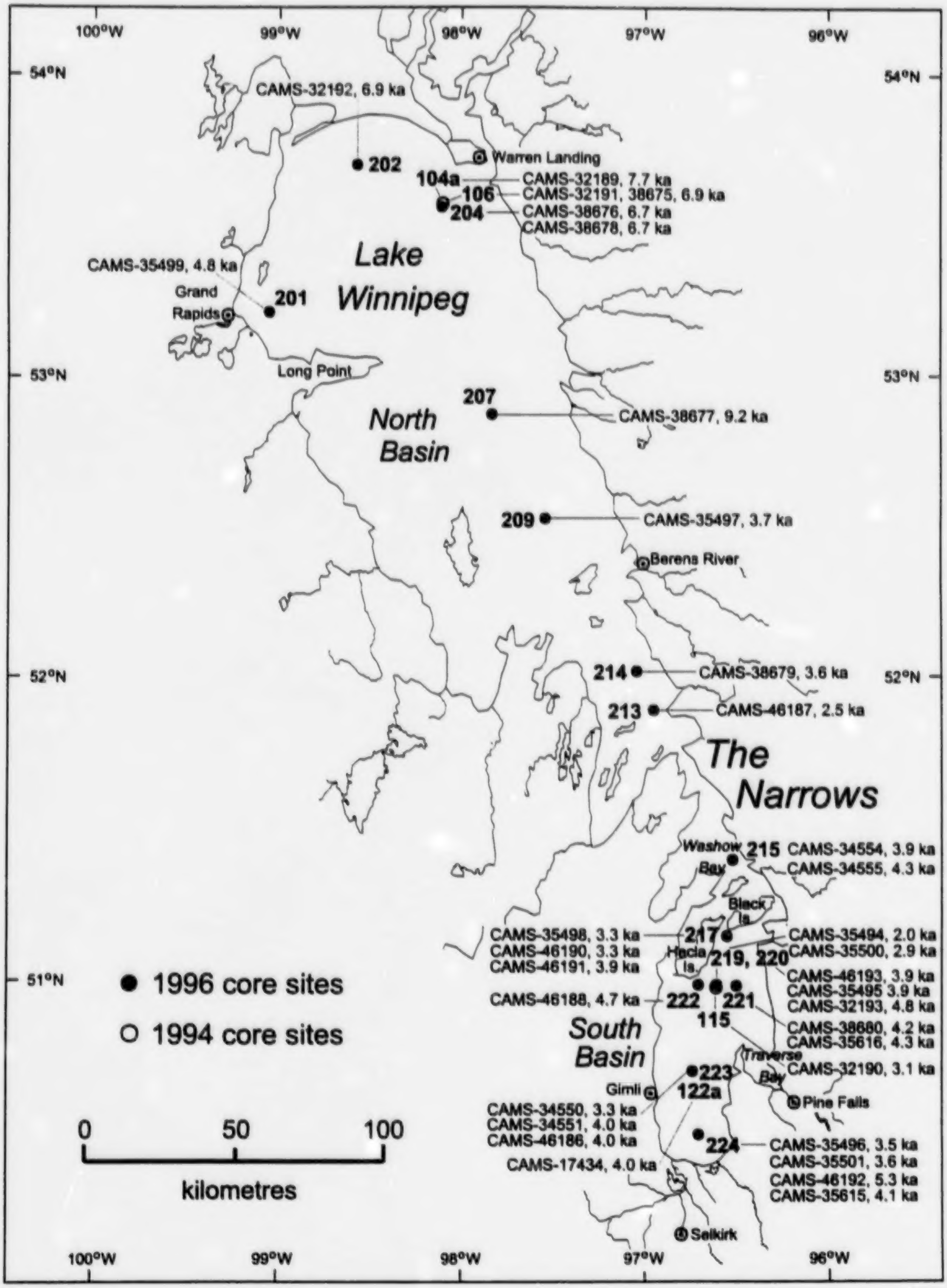
100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
CAMS-32192, 6.9 ka
202
Warren Landing
104a
106
204
CAMS-32189, 7.7 ka
CAMS-32191, 38675, 6.9 ka
CAMS-38676, 6.7 ka
CAMS-38678, 6.7 ka
Lake Winnipeg
CAMS-35499, 4.8 ka
Grand Rapids
201
Long Point
North Basin
207
CAMS-38677, 9.2 ka
209
CAMS-35497, 3.7 ka
Berens River
214
CAMS-38679, 3.6 ka
213
CAMS-46187, 2.5 ka
The Narrows
Washow Bay
215
CAMS-34554, 3.9 ka
CAMS-34555, 4.3 ka
Black Is.
CAMS-35498, 3.3 ka
CAMS-46190, 3.3 ka
CAMS-46191, 3.9 ka
217
Hecla Is.
219, 220
CAMS-35494, 2.0 ka
CAMS-35500, 2.9 ka
CAMS-46193, 3.9 ka
CAMS-35495 3.9 ka
CAMS-32193, 4.8 ka
CAMS-46188, 4.7 ka
222
221
115
CAMS-38680, 4.2 ka
CAMS-35616, 4.3 ka
South Basin
Traverse Bay
CAMS-32190, 3.1 ka
223
Gimli
122a
Pine Falls
CAMS-34550, 3.3 ka
CAMS-34551, 4.0 ka
CAMS-46186, 4.0 ka
CAMS-17434, 4.0 ka
224
CAMS-35496, 3.5 ka
CAMS-35501, 3.6 ka
CAMS-46192, 5.3 ka
CAMS-35615, 4.1 ka
Selkirk
● 1996 core sites
○ 1994 core sites
0
50
100
kilometres

Figure 1. Lake Winnipeg 1994 and 1996 radiocarbon dated core sites

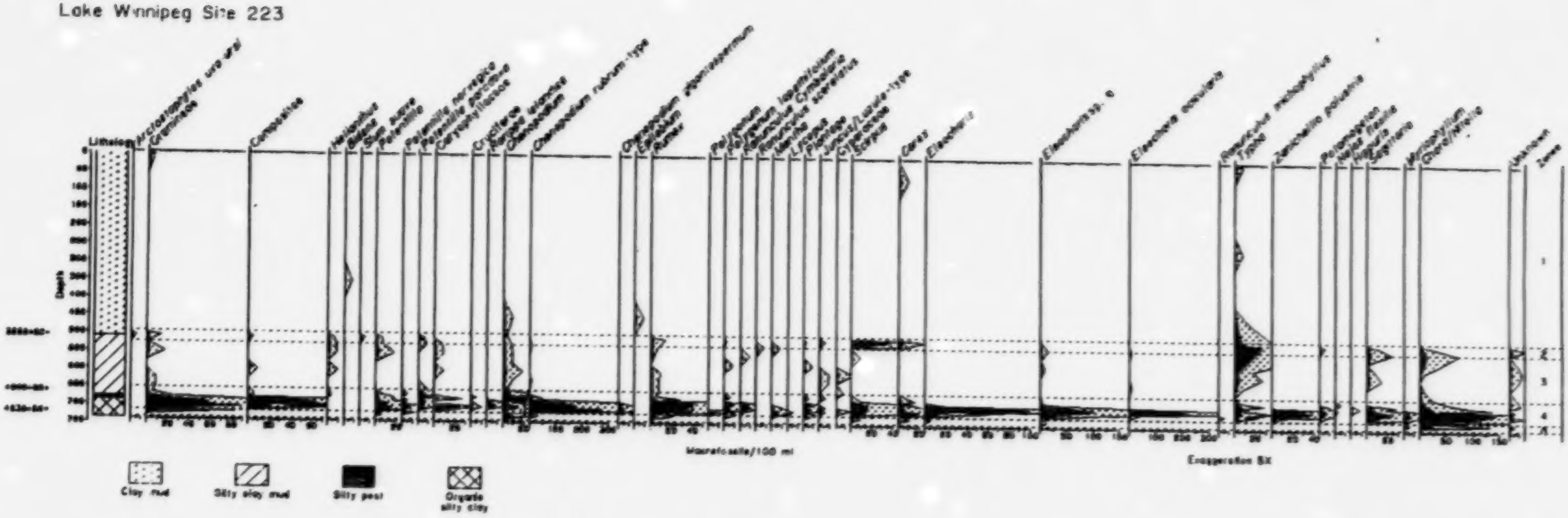

Figure 2. Macrofossil abundances, Lake Winnipeg core 223.

8.4 Composite pollen stratigraphy of Lake Winnipeg

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INTRODUCTION

Samples from three piston cores (103, 106, 105) recovered from offshore sediments in the north basin of Lake Winnipeg were processed to (a) derive a composite pollen stratigraphy for Lake Winnipeg and underlying Lake Agassiz sediments and to correlate this pollen stratigraphy with dated pollen records on land, (b) to determine vegetation and climate history for the basin as a whole, (c) to determine evidence for and timing of Lake Agassiz and Lake Winnipeg deposition and (d) to correlate with regional lake level changes. Samples for pollen analysis were extracted from the cores and forwarded to the authors by the project leaders. Core locations are shown in Todd (1999). The cores collectively comprise a composite lithostratigraphy of Lake Winnipeg and Lake Agassiz sediments and underlying till based on seismostratigraphic correlation of the cores (Todd et al., 1997).

METHODS

The sediment samples were treated using standard palynological methods (Faegri and Iversen, 1975) including acid digestion, acetolysis and suspension in silicone oil. Exotic pollen were added prior to treatment and these were counted along with the fossil pollen to determine overall pollen/spore concentrations per cm^3 of sediment. The processed sediment was sieved according to the method of Cwynar et al (1979) to concentrate the fossil pollen. The pollen sum, from 220 to 350 tree, shrub and herb pollen, served as the basis upon which pollen percentages were calculated. The composite pollen diagrams show analyses done on the entire length of core 103 and on segments of cores 106 (4 to 7 m) and 105 (2 to 5 m). The pollen stratigraphy is visually zoned into five pollen assemblage zones (Fig. 1).

LAKE WINNIPEG COMPOSITE POLLEN STRATIGRAPHY

Pollen zone 1 (basal part of core 105) is dominated by herb pollen with *Artemisia (*maximum 36%) clearly the dominant taxon. Zone 2 (upper part of core 105, lower half of core 106) shows an assemblage characterized by still high percentages of *Artemisia* and significant increases in *Ambrosia* and Chenopodiineae. *Pinus* and *Picea* increase upwards in the zone with *Pinus* reaching close to 35% maximum in places.

The zone 2/3 boundary marks a major decrease in *Pinus* and *Picea* and an equally major increase in *Betula* and in the grassland taxa *Ambrosia* and *Artemisia;* Chenopodiineae and Gramineae remain high and relatively unchanged across the zone boundary. The basal part of core 103 shows higher *Picea* and *Pinus* and, with the exception of Gramineae, lower herbs than in the previous zone making it equivalent to zone 2 (basal half of core 106). Pollen zone 3 of core 106 is apparently absent in core 103, consistent with an unconformity recorded in the lithostratigraphy of core 103 at 686 cm (Lewis et al., this volume).

Zone 4 is distinguished by a major pollen change, the replacement of herbs by abrupt increases in *Pinus*, *Alnus* and in the alga *Pediastrum*. Zone 5 has *Picea* and *Pinus* reaching maximum percents and pollen concentrations increasing to peak values at the top of the sequence.

Excluding the lowest and highest values, pollen concentrations average 4600 grains/cm^3 throughout zones 1 and 2. Pollen concentrations decrease in zone 3 to an average 1800 grains/cm^3. Concentrations increase abruptly across the unconformable zone 2/4 boundary to 40,000 grains/cm^3 corresponding to the change from herb to tree pollen dominance. After reaching minimum values of 4700 grains/cm^3 in zone 4, concentrations increase steadily upwards in zone 5 reaching a maximum 115,000 grains/cm^3 prior to declining to 51,000 grains/cm^3 at the surface.

CHRONOLOGY

The offshore cores examined in this report lack suitable organic remains such as seeds and leaves for Accelerator Mass Spectrometry (AMS) radiocarbon dating, and bulk sediment dating by conventional or AMS dating is unreliable (Vance and Telka, 1998). Hence, to develop a chronology we correlated the Lake Winnipeg/Lake Agassiz pollen stratigraphy with nearby dated sequences from the west side of the basin, Riding Mountain (Ritchie, 1964) and Grand Rapids (Ritchie and Hadden, 1975). The Hayes Lake (McAndrews, 1982) and Nungesser Lake (Terasmae, 1967) pollen records on the east side of Lake Winnipeg basin were used to map mid-Holocene vegetation boundaries. ^{14}C dates or derived age estimates for the zone boundaries and pollen horizons at Riding Mountain and Grand Rapids are applied to similar identified zone boundaries and pollen horizons in the Lake Winnipeg cores 103 and 106. These age estimates and the basis for the onshore-offshore chronology correlations are shown in Table 1.

The Riding Mountain chronology provides a valid correlation for the older Lake Winnipeg record (early Agassiz history). The *Picea* peak at 565 cm in core 106 is similar to the basal *Picea* peak at Riding Mountain and therefore dates 10,000 BP. The zone 2/3 boundary in core 106 is equivalent to Riding Mountain zone IV/III boundary which dates about 9300 BP.

The Grand Rapids chronology provides a reliable correlation for the late phase of Lake Agassiz and the transition to Lake Winnipeg. Basal sand below gyttja at Grand Rapids is dated at 7220 BP. This date provides a minimum age for (a) isolation of the Grand Rapids lake site from the waters of Lake Agassiz and (b) retreat of the late phases (Phases 5 and 6) of Lake Agassiz from the northern Lake Winnipeg area (Klassen, 1983). The 7220 BP Grand Rapids pollen spectrum is characterized by moderately high *Picea, Pinus* and *Juniperus* prior to the rise in *Alnus*. This spectrum correlates with the moderately high *Picea, Pinus* and *Juniperus* percentages at the base of core 103 (zone 2). *Alnus* starts to increase just below the zone 2/4 boundary in core 103 and reaches peak percentages in overlying zone 4. The unconformable (Agassiz/Winnipeg) zone 2/4 boundary correlates with the zone I/II boundary at Grand Rapids, which dates approximately 5700 BP based on rates of sedimentation.

VEGETATION HISTORY

The pollen assemblage zones are interpreted in terms of vegetation composition from known analogues. The lowest assemblage zones 1 and 2 contain a mixture of spruce, pine, birch and willow and taxa within the grasses, chenopods and composites. Pollen concentration is low throughout. These assemblage zones are indicative of spruce parkland vegetation with treeless openings occupied by sagebrush, ragweed, grasses, chenopods and other prairie herbs. However, zone 1 with high *Artemisia* (up to 36%) and occurrences of *Oxyria digyna* at the base of the Lake Agassiz rhythmites just above till might be interpreted as being more tundra-like. The hardwood pollen of oak and elm were probably blown into the lake from distant sources to the south. The spruce maximum suggests spruce was probably more widespread around the north basin at 10 ka than at any time previously.

Applying Lichti-Federovich and Ritchie's (1968) value of 60% herb pollen as the threshold limit in the delineation of grassland spectra identifies pollen zone 3 as border-line grassland. However, we consider the zone 3 dominance of grassland indicators (total herbs range between 50 and 76%) to be sufficiently representative of grassland considering that Lake Winnipeg is a large lake and is subject to inherent factors (i.e. presence of water currents and probability of erosion and redeposition and loss of sediment and pollen) that characterize such large bodies of water often resulting in difficulties of interpretation (Davis et al, 1969; Jacobson and Bradshaw, 1981; Pennington, 1973). Mean percentages of 33.9%, 12.4% and 57.3 % for total tree, shrub and herb pollen, respectively, in zone 3 are not unlike the present-day values in Devils Lake, North Dakota, a typical closed, saline lake situated within the prairie-dominated region of the Great Plains (Jacobson and Engstrom, 1989). Total tree, shrub and herb pollen per cents in Main Bay, the largest basin (50 km^2) in Devils Lake are 33.5%, 4.1% and 52%, respectively. While Devils Lake is a large lake, but not in the size range of Lake Winnipeg, the close comparison of the tree, shrub and herb percentages, nevertheless, supports our zone 3 interpretation.

The zone 3 pollen assemblage is equivalent to zone 3b in Hayes Lake (McAndrews, 1982) where an early to mid-Holocene *Pinus* dominance and enhanced percentages of herbs (*Artemisia, Ambrosia,* other composites, Gramineae and Chenopodiinaceae) are interpreted to represent open (grassy jack pine-poplar) woodland. Open-woodland conditions probably also existed at Nungesser Lake (Terasmae, 1967) based on the early to mid-Holocene *Picea-Pinus and Betula* succession in combination with the same herb indicators.

The extremely low pollen concentrations in zone 3 are tied to the decrease in tree percentages and a real decrease in tree pollen deposition at this time. Ritchie (1969) shows a similar decrease in total pollen influx during the mid-Holocene period of prairie dominance at Riding Mountain where prairie was succeeded by forest and a 4-fold increase in pollen influx rates.

The zone 2/4 boundary in core 103 shows an apparent abrupt change to forest including pine, birch, alder and poplar. It corresponds with the 5700 BP and 6000 BP transitions to forest at Grand Rapids and Riding Mountain, respectively, and with the subtle change from low pine to high pine and oak (3b/3c zone boundary) at Hayes Lake (McAndrews, 1982). The sudden influx of *Pediastrum* and 10-fold increase in pollen concentration across the zone 2/4 boundary in core 103 correspond with the sediment change from Agassiz to Lake Winnipeg deposition. The absence of pollen zone 3 indicates an unconformable sequence at the Agassiz-Winnipeg contact. The unconformity may have encompassed up to 1520 years (7220-5700 BP), if our method of dating through core correlation is correct.

The vegetation of zone 4 time comprised a mixed forest of spruce, pine, alder, poplar with birch and willow. In Zone 5 pine is at its maximum and spruce reappears again as a dominant component in the local forest. Since about 4000 BP and 2500 BP (comparison with Grand Rapids and Riding Mountain sites, respectively) the vegetation was probably not unlike the modern-day boreal forest in the area. The upward increase in pollen concentration to peak values of 115,000 grains/cm^3 in zone 5 reflects the post-4 ka dominance of *Picea* and *Pinus*.

CLIMATIC DEDUCTIONS

The large expanse of Lake Agassiz likely generated a local, cool climate (Anderson and Lewis, 1992) which would have favoured spruce parkland vegetation in areas bordering the north basin during zones 1 and 2 time. The spruce dominance suggests the climate had started to warm as early as 10,000 BP.

The switch to grassland at approximately 9.3 ka at Riding Mountain and its inferred presence in North Basin core 106 represents an expansion of grassland northward and eastward to the Lake Winnipeg basin. The grassland dominance corresponds to the early Holocene interval of increased aridity, a time when mean annual temperatures may have exceeded current conditions by 0.5° to 1.5°C to as much as 3°C and mean annual precipitation was reduced by 65 mm to as much as 50 mm below present values (Vance et al., 1995). The period of maximum warmth and dryness and corresponding increase in evapo-transpiration rates caused many lakes in the southern Prairie region to dry up completely and others to become hypersaline playas (Vance et al., 1995, 1997).

The core 106 pollen evidence in combination with the Grand Rapids record shows grassland enclosed South Basin but only the southern part of North Basin up until 6.5 ka (Fig. 3). The 6.5 ka contour is approximated east of Lake Winnipeg because of the lack of available sites. The 6.5 ka record at Hayes Lake indicates that parkland had separated grassland and forest east of Lake Winnipeg. Grassland and parkland limits are extended southeast of Lake Winnipeg where they join the equivalent prairie and oak-savanna easternmost limits in the midwest United States (Wright, 1993). Figure 3 shows the 6.5 ka grassland-forest boundary proposed by Ritchie (1976) and our proposed revision to the 6.5 ka grassland and parkland limits east and southeast of Lake Winnipeg based on data presented here.

Climatic conditions deteriorated gradually after 6000 BP and more so after 4000 BP and 2500 BP (comparisons with the records at Riding Mountain and Grand Rapids, respectively) with the invasion of grassland by mixed forest and gradual change to more boreal conditions. The onset of the late Holocene cooler/wetter climate was accompanied by gradually to rapidly rising lake levels in the southern Prairies. Since that time, lake levels have fluctuated but never reached the low-water episodes of the middle Holocene (Vance et al., 1993, 1997).

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FIGURES

Figure 1. Composite pollen diagram for cores 103, 106 and 105 in the North Basin, Lake Winnipeg. The diagram shows alternate chronologies based on correlation with the dated pollen records at Riding Mountain (Ritchie, 1964) and Grand Rapids (Ritchie and Hadden, 1975) sites in Manitoba. The broken line at 60% in the "Total Grassland Indicators" column is the threshold limit for delineation of grassland (after Litchi-Federovich and Ritchie, 1968); the solid line at 52% denotes percent of equivalent, present-day total grassland indicators in Devils Lake, North Dakota (from Jacobson and Engstrom, 1989). The value 115,000 in the concentration profile is the maximum concentration of pollen and spores/cm^3.

Figure 2. Abbreviated pollen diagrams for Riding Mountain and Grand Rapids from Ritchie (1964) and Ritchie and Hadden (1975).

Figure 3. The green line is the present-day grassland limit in Canada (from Rowe, 1972) and United States (from Küchler, 1964). The yellow and red lines are approximate grassland and parkland limits, respectively, at 6.5 ka. Figure shows Ritchie's (1976) 6.5 ka grassland and parkland limits and our proposed extensions of these limits in the area east and southeast of Lake Winnipeg. The grassland limit crosses to the east side of Lake Winnipeg and continues south across the Canada-U.S. border where it joins the equivalent easternmost prairie limit in midwest United States delineated in Wright (1993) and from pollen evidence at Elk Lake (Whitlock et al., 1993) and Billy's Lake in central Minnesota (Jacobson and Grimm, 1986). The parkland limit lies east of and somewhat parallels the grassland boundary. Parkland persisted at Hayes Lake (McAndrews, 1982) based on positive pollen evidence (grassy jack pine-poplar woodland) there. However, negative pollen evidence at Nungesser Lake (Terasmae, 1967) and Rattle Lake (Björck, 1985) indicates

parkland was absent at these sites, although the mid-Holocene warm climate may have favoured some hardwoods (oak, elm, ash) and caused the prairie expansion to come closer to Rattle Lake (Björck, 1985). The parkland limit extends across the Canada-U.S. border where it is equivalent to the easternmost oak-savanna limit in midwest United States as suggested in Wright (1993) and from pollen evidence at Myrtle Lake, Rossburg Bog and Jacobson Lake in eastern Minnesota (Wright and Watts, 1969). The wide gap between the present-day grassland boundary and the 6.5 ka grassland and parkland limits represents the extent of the expanded mid-Holocene climate as it affected the Lake Winnipeg drainage basin at 6.5 ka.

Table 1. Alternate chronologies for the Lake Winnipeg basin sediments based on pollen correlation with ^{14}C dated pollen records at Riding Mountain and Grand Rapids, Manitoba.

Core/Depth	**Pollen Feature**	**Riding Mountain Chronology (Years BP)**	**Grand Rapids Chronology (Years BP)**
103 / 410 cm	*Picea* increase (zone 4/5a)	2500-3000	4000
103 / 686 cm	Grassland-forest boundary (zone 2/4)	6000	5700
103 / 705-735 cm	Pre-*Alnus*, moderately high *Picea* and *Pinus* (zone 2)		7220
106 / 525 cm	Parkland-grassland boundary (zone 2/3)	9300	
106 / 565 cm	*Picea* peak (zone 2)	10000	

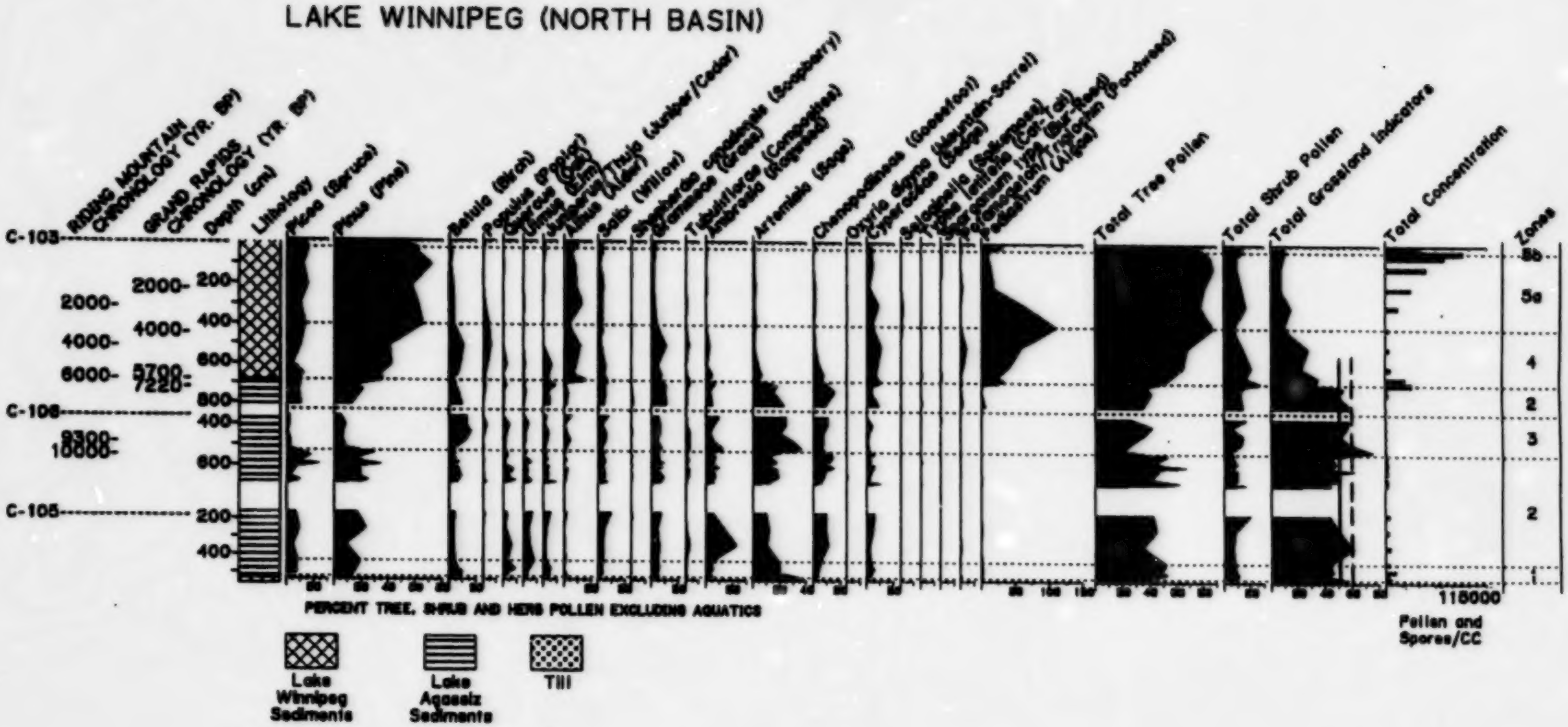
LAKE WINNIPEG (NORTH BASIN)
RIDING MOUNTAIN CHRONOLOGY (YR. BP)
GRAND RAPIDS CHRONOLOGY (YR. BP)
Depth (cm)
Lithology
Picea (Spruce)
Pinus (Pine)
Betula (Birch)
Populus (Poplar)
Quercus (Oak)
Ulmus (Elm)
Juniperus/Thuja (Juniper/Cedar)
Alnus (Alder)
Salix (Willow)
Shepherdia canadensis (Soapberry)
Gramineae (Grass)
Tubuliflorae (Compositae)
Ambrosia (Ragweed)
Artemisia (Sage)
Chenopodiineae (Goosefoot)
Oxyria digyna (Mountain-Sorrel)
Cyperaceae (Sedge)
Selaginella (Spikemoss)
Typha latifolia (Cat-tail)
Sparganium type (Bur-Reed)
Potamogeton/Triglochin (Pondweed)
Pediastrum (Algae)
Total Tree Pollen
Total Shrub Pollen
Total Grassland Indicators
Total Concentration
Zones
C-103
C-106
C-105
2000-
4000-
6000-
9300-
10000-
5700-
7220-
200-
400-
600-
800-
5b
5a
4
2
3
2
1
PERCENT TREE, SHRUB AND HERB POLLEN EXCLUDING AQUATICS
118000
Pollen and Spores/CC
Lake Winnipeg Sediments
Lake Agassiz Sediments
Till

Figure 1.

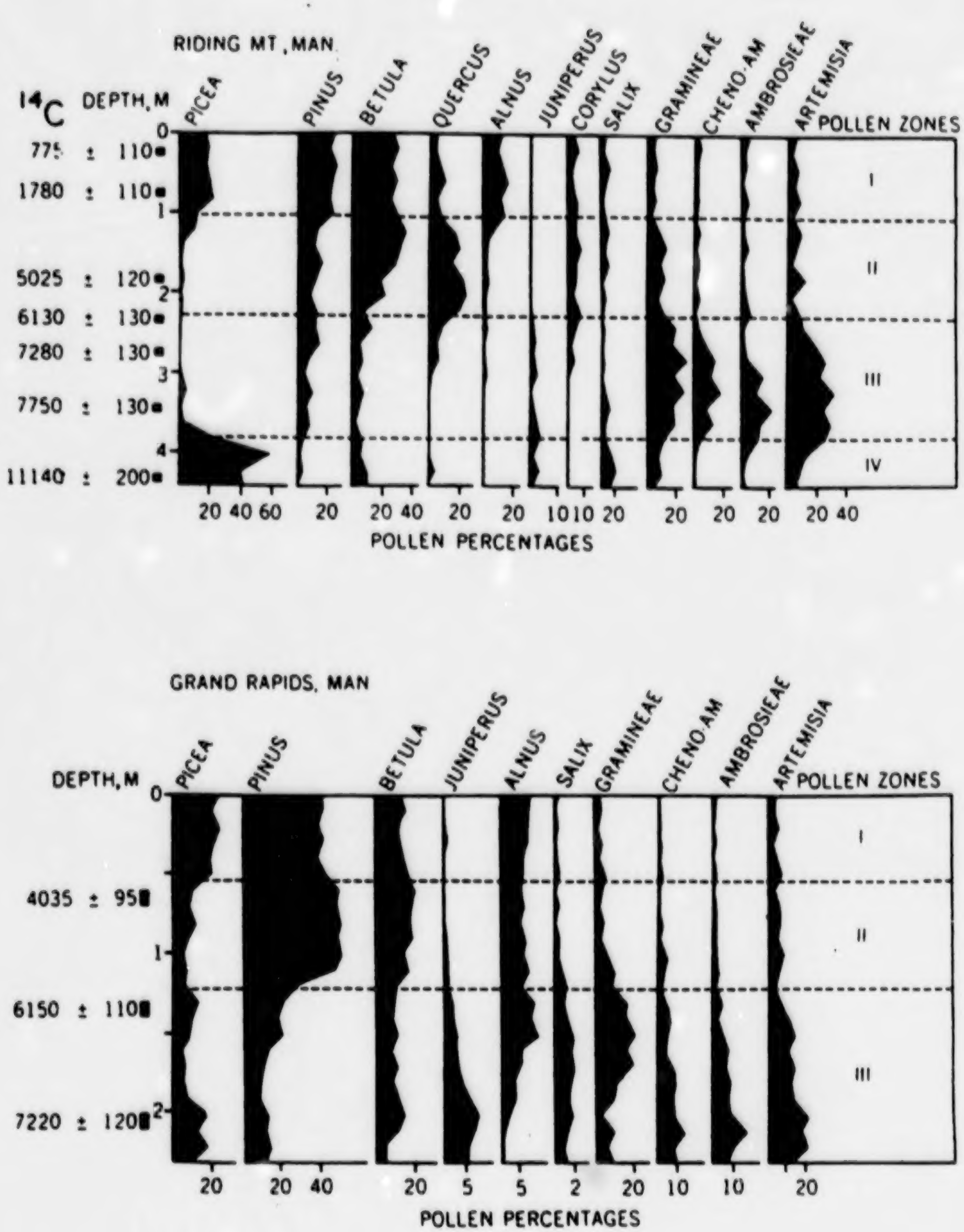
RIDING MT., MAN.
14C
DEPTH, M
775 ± 110
1780 ± 110
5025 ± 120
6130 ± 130
7280 ± 130
7750 ± 130
11140 ± 200
0
1
2
3
4
PICEA
PINUS
BETULA
QUERCUS
ALNUS
JUNIPERUS
CORYLUS
SALIX
GRAMINEAE
CHENO-AM
AMBROSIEAE
ARTEMISIA
POLLEN ZONES
I
II
III
IV
20 40 60
20
20 40
20
20
10
10
20
20
20
20
20 40
POLLEN PERCENTAGES
GRAND RAPIDS, MAN
DEPTH, M
0
1
2
4035 ± 95
6150 ± 110
7220 ± 120
PICEA
PINUS
BETULA
JUNIPERUS
ALNUS
SALIX
GRAMINEAE
CHENO-AM
AMBROSIEAE
ARTEMISIA
POLLEN ZONES
I
II
III
20
20 40
20
5
5
2
20
10
10
20
POLLEN PERCENTAGES

Figure 2.

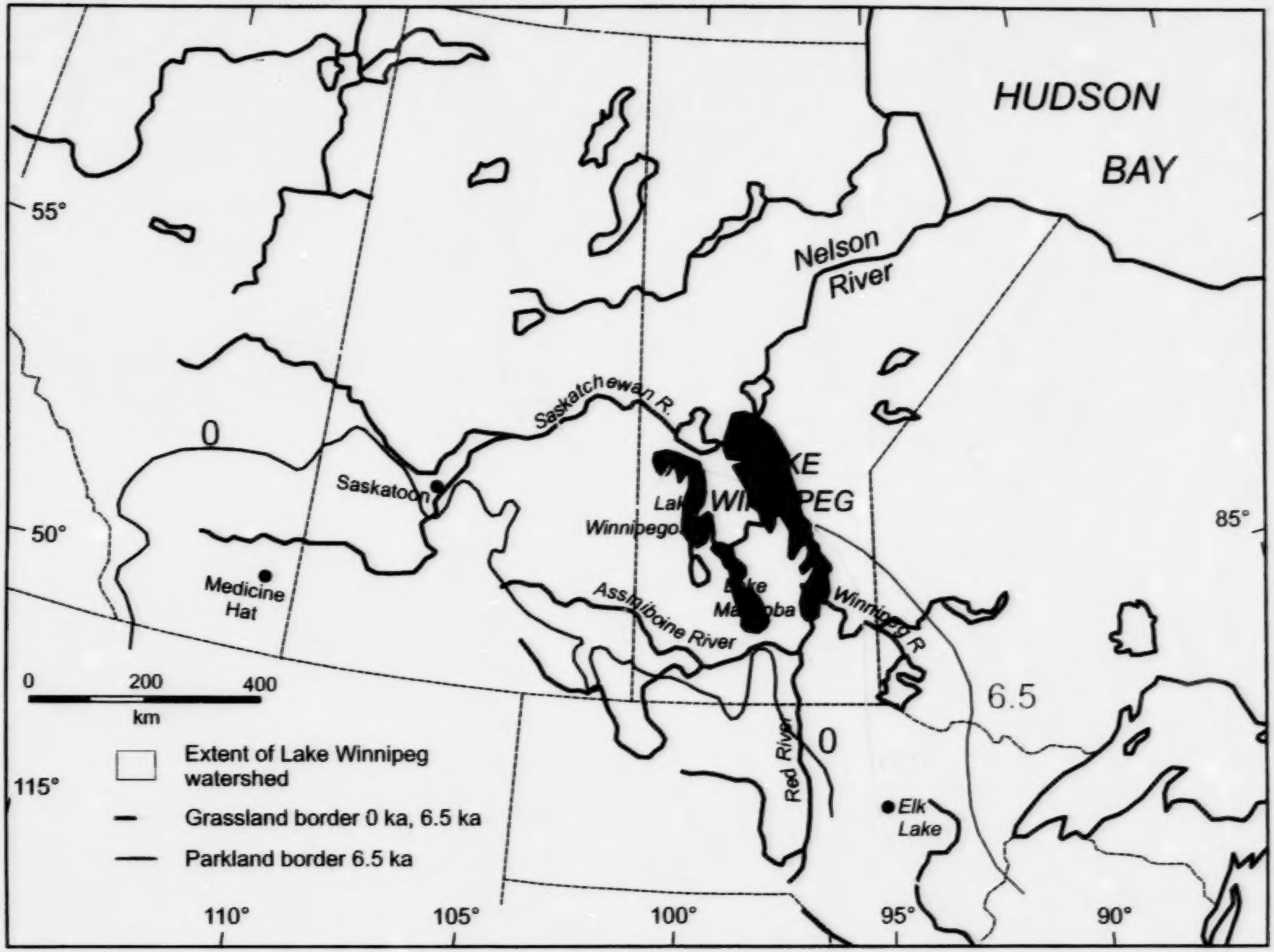
HUDSON
BAY
Nelson
River
Saskatchewan R.
KE
WI PEG
Lak
Winnipego
ke
Ma oba
Saskatoon
Medicine
Hat
Assiniboine River
Winnipeg R.
Red River
Elk
Lake
0
0
6.5
55°
50°
85°
115°
110°
105°
100°
95°
90°
0
200
400
km
Extent of Lake Winnipeg watershed
Grassland border 0 ka, 6.5 ka
Parkland border 6.5 ka

Figure 3.

9. Shoreline evolution

9.1 Lake Winnipeg coastal submergence and tree-ring responses to water-level changes

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OBJECTIVES

Previous work by Lewis and Todd (1996) has shown that Lake Winnipeg has steadily increased in area since its inception, after the drainage of Lake Agassiz, approximately 8000 years ago. The lake level rise throughout the Holocene is thought to be the result of isostatic uplift of the northern outlets of the basin, first at Warren Landing and later at Whiskey Jack Narrows. A shoreline survey by Forbes and Frobel (1996) confirmed the transgressive character of South Basin as concluded by Nielsen and Conley (1994), Nielsen (1998) and Lewis and Todd (1996). More importantly however, Forbes and Frobel also found evidence of recent submergence along the shores of North Basin suggesting Lake Winnipeg is presently undergoing basin-wide transgression. This basin-wide transgression of the Lake Winnipeg shoreline is not easily explained by isostatic tilting. It is therefore postulated that low amplitude basin-wide water-level fluctuations due to climatic variations are superimposed on the more prominent southward transgression of the lake as the result of isostatic tilting.

The tree-stump sampling program was undertaken to investigate recent water level changes, possibly due to climate changes at the end of the Little Ice Age. The lakeshore survey was undertaken to look for sites with drowned forests in both North and South basins to supplement those described previously (Nielsen, 1998). Radiocarbon or dendrochronological dating of submerged trees from these sites may determine the rate of the recent water-level rise in Lake Winnipeg.

In addition, a pilot project was initiated to determine if tree-ring width measurements can be used to reconstruct the history of water-level fluctuations prior to 1913 when instrumental recording began.

SAMPLING

Two, one day, low altitude helicopter surveys of the east and west shores of Lake Winnipeg on August 1, 1996 and August 1, 1997 revealed widespread evidence of shoreline transgression. Submerged or "drowned forests", similar to those described by Nielsen and Conley (1994) and Nielsen (1998) along the south shore of South Basin, were discovered at six sites between Warren Landing and Traverse Bay, on the east side of the lake in 1996, and at nine sites on the west side between Grand Rapids and Matheson Island in 1997 (Fig.1).

The 1996 survey of the shoreline, carried out as part of the Lake Winnipeg Project Phase II survey, presented an opportunity to sample the drowned forests at three of the six sites on the east side of the lake. Stem discs from 57 subfossil, prone conifer logs and *in situ* stumps were collected from the drowned forests exposed on the foreshore at Spider Islands, Marchand Point and Observation Point. At Observation Point, 15 stumps were collected on each of the north and south sides of the headland. Observation Point (north) had been sampled previously in 1993 (Nielsen and Conley, 1996). The location, number of samples, date of collection and the approximate elevation of the root crowns of the stumps from each site are listed in Table 1. In addition, 34 modern driftwood samples were collected from the beach at Disbrowe Point, approximately 10 km northwest of Berens River. The driftwood logs are believed to have been derived from the modern forest eroding along the shore, 5 kilometres to the north. Eight buried logs were also collected from under the dune ridge exposed on the north side of Disbrowe Point.

As part of the orientation survey to look at the effects of rising water levels on tree-ring widths, five dead or dying tamaracks (*Larix laricina* (Du Roi) K. Koch) were sampled from the beach and the fen, immediately behind the beach, at Observation Point (south).

DATING

Radiocarbon dating

Tree stumps on the foreshore are believed to have died when their roots became permanently submerged as they are now rooted close to or below mean lake level of 217.4 m. To determine the rate of water-level rise two samples from each of Spider Islands, Marchand Point and Observation Point (south) were submitted for radiocarbon dating. Two logs from under the dunes at Disbrowe Point were also submitted for radiocarbon dating to determine the age of the washover and the maximum age of the sand dunes.

Tree-ring analysis

Cross dating of tree-ring width measurements on *in situ* drowned tamarack stumps and prone tamarack logs with those of the 34 modern samples from Disbrowe Point and the five trees from Observation Point (south), to more accurately determine the rate of water-level rise, is in progress.

RESULTS

Radiocarbon dating

New radiocarbon dates on rooted stumps and prone logs from approximately the same elevation and setting, at Spider Islands, Marchand Point and Observation Point (south) yielded radically different ages (Table 2). All samples were collected from the foreshore in 20-50 cm of water and approximately the same elevation. The Spider Island dates are 255 and 390 yrs. B.P. whereas the Marchand Point and Observation Point (south) dates range between 1,100 and 2,050 yrs. B.P. suggesting two different origins for the logs.

The Spider Island stumps are believed to be situated on the foreshore as the result of transgression of the lake into an area forested by living trees (Figure 2A). The trees were growing in the area behind the beach, at an elevation slightly above the level of the lake, similar to that described by Nielsen and Conley (1994) in Netley Marsh. The elevation of the root crowns and ages of the Spider Islands stumps are comparable to those from sites in South Basin confirming a water level rise of approximately 20 cm/century as determined by Nielsen (1998). If the transgression was the result of isostatic tilting the rate of water-level rise would decrease toward the north, with no evidence of transgression at the outlet at Whiskey Jack Narrows.

The relatively older stumps and logs on the foreshore at Marchand Point and Observation Point (south) are thought to have been exhumed from previously deposited peat deposits that accumulated in the fen behind the beach. As the fen grew, due to a rise in the water table which may or may not be related to the rising lake level, trees growing in the fen died and were subsequently buried by peat (Figure. 2B). Consequently, the trees were dead before they became buried by the beach and exposed on the foreshore and are not directly related to the transgression of the lake.

Tree-ring analysis

The stem discs from the five modern tamaracks from Observation Point (south) were prepared using standard tree-ring dating techniques (Nielsen et al., 1995). Tree-ring width measurements on the five trees and the relative water-level fluctuations in Lake Winnipeg from 1913 to 1996 are shown in figure 3. One tree (97-5) grew on the sandy beach ridge and was alive at the time of sampling. The other four trees were collected from the treed fen behind the beach; two trees were alive but severely stressed (97-3 and 97-4) whereas, the other two (97-1 and 97-2) were dead.

The five tamaracks were easily cross dated using tree-ring width measurements. The curves clearly indicate that **wide** rings are related to periods of **low** water level (Fig. 3). During the 1930s and 1940s when Lake Winnipeg water levels were low, all five trees showed accelerated growth. The live tree from the beach (97-5) also shows increased growth in 1977 and, in part, the late 1980s and early 1990s when lake levels were low.

Only one tree-ring curve (97-1) extends significantly beyond 1913, when systematic instrumental water-level recording started on Lake Winnipeg. Ring widths in this tree are initially, relatively wide during the 1890s and early 1900s, though not as wide as during the 1930s and 1940s, and then decrease, suggesting a slight water level rise in the later part of the last century and early part of this century. This conclusion is supported by the analysis of the agricultural climate of southern Manitoba by Allsopp (1977) who found the period from 1883 to 1894 to be generally cool and dry. Average precipitation and cool temperatures were characteristic from 1895 to 1899 and the first decade of the twentieth century had slightly wet or average conditions.

CONCLUSIONS AND RECOMMENDATIONS

Drowned forests have been identified from a number of sites along the shores of North and South basins indicating Lake Winnipeg is transgressing in all directions and confirming the observations of Forbes and Frobel (1996).

Radiocarbon dates on tamarack logs from the drowned forest, on the foreshore at Spider Islands in North

Basin, are comparable with those obtained from similar elevations in South Basin (Nielsen, 1998) suggesting the observed water-level rise is due to climate change.

Radiocarbon dating of *in situ* stumps and prone logs, from drowned forest sites indicate some trees died recently as the result of transgression whereas others are exhumed older, dead trees that have been buried for centuries in thin peat deposits and are unrelated to lake level fluctuations.

Tree-ring analysis of tamaracks from the fens backing the transgressive beaches of Lake Winnipeg is a viable technique for determining water levels prior to 1913 when instrumental recording started. By carefully selecting older trees it should be possible to construct a water-level record for the 19th century using tree rings.

Additional sites with submerged tree stumps should be sampled. Stem discs should be dated by dendrochronology to give a precise rate of inundation of the lake which is not possible with radiocarbon dating.

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Figure 2.	Schematic model illustrating the origins of 'drowned forests' the foreshore of Lake Winnipeg by transgression into, (A) a living forest, and (B) forested peat with previously dead *in situ* stumps and prone logs.
Figure 3.	Tree-ring curves for tamaracks at Observation Point and relative Lake Winnipeg water levels from 1913 to 1996.

Table 1: *Namao* 96-900 wood sample inventory.

Sample Site	Latitude Longitude	Date Sampled	Number of Logs	Approximate Elevation
Spider Islands	53°30'N 97°43'W	August 25	14	217.7
Marchand Point	52°49'N 97°22'W	August 26	13	217.2
Observation Point (south)	51°04'N 96°26'W	August 14	15	217.5
Observation Point (north)	51°04'N 96°26'W	August 29	15	217.5
Observation Point (south)	51°04'N 96°26'W	August 29	5 modern	—
Disbrowe Point	52°25' 97°08'W	August 17	8 dune	—
Disbrowe Point	—	August 17	34 modern	—

Table 2: Radiocarbon dates from the shores of Lake Winnipeg.

Sample sites	Lab. No.	^{14}C age years B.P.*	Calibrated years B.P.*	Calendar years B.P.	Material	Elevation (m)
Sider Islands	BGS-1906	390±70	475	1475	*Larix*	217.7
	BGS-1907	255±75	295	1655	*Larix*	217.7
Marchand Point	BGS-1908	2,050±80	1,990	40 B.C.	*Larix*	217.2
	BGS-1909	1,100±75	980	980	*Larix*	217.2
Observation Point	BGS-1912	1,795±75	1,710	240	*Larix*	217.5
	BGS-1913	1,810±80	1,715	235	*Larix*	217.5
Disbrowe Point	BGS-1910	130±70	130	1820	?	—
	BGS-1911	260±75	295	1655		

*Radiocarbon years are expressed as years before 1950.

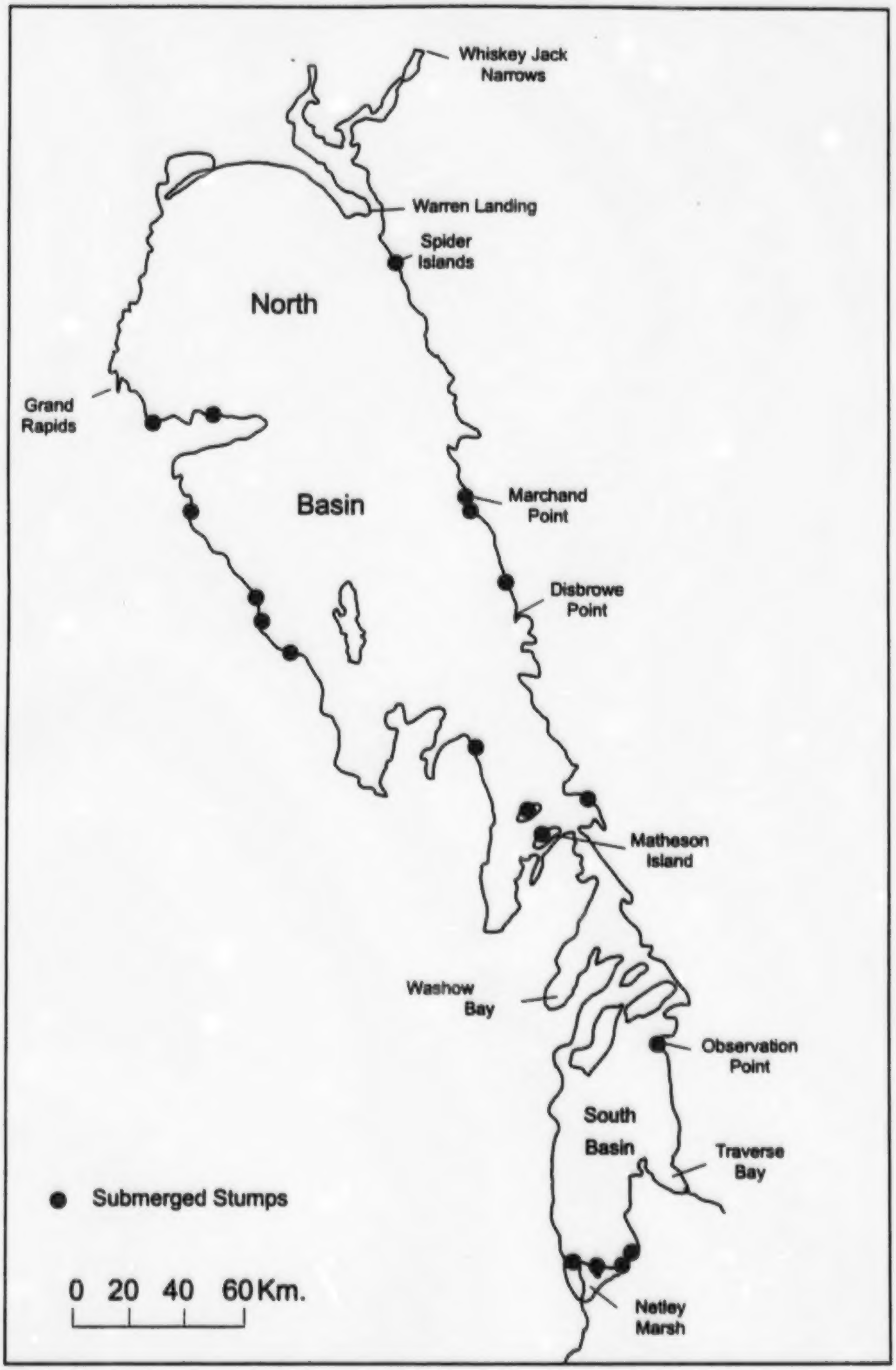
Whiskey Jack Narrows
Warren Landing
Spider Islands
North
Basin
Grand Rapids
Marchand Point
Disbrowe Point
Matheson Island
Washow Bay
Observation Point
South Basin
Traverse Bay
● Submerged Stumps
0 20 40 60 Km.
Netley Marsh

Figure 1. Sites with submerged tree stumps on the shores of Lake Winnipeg.

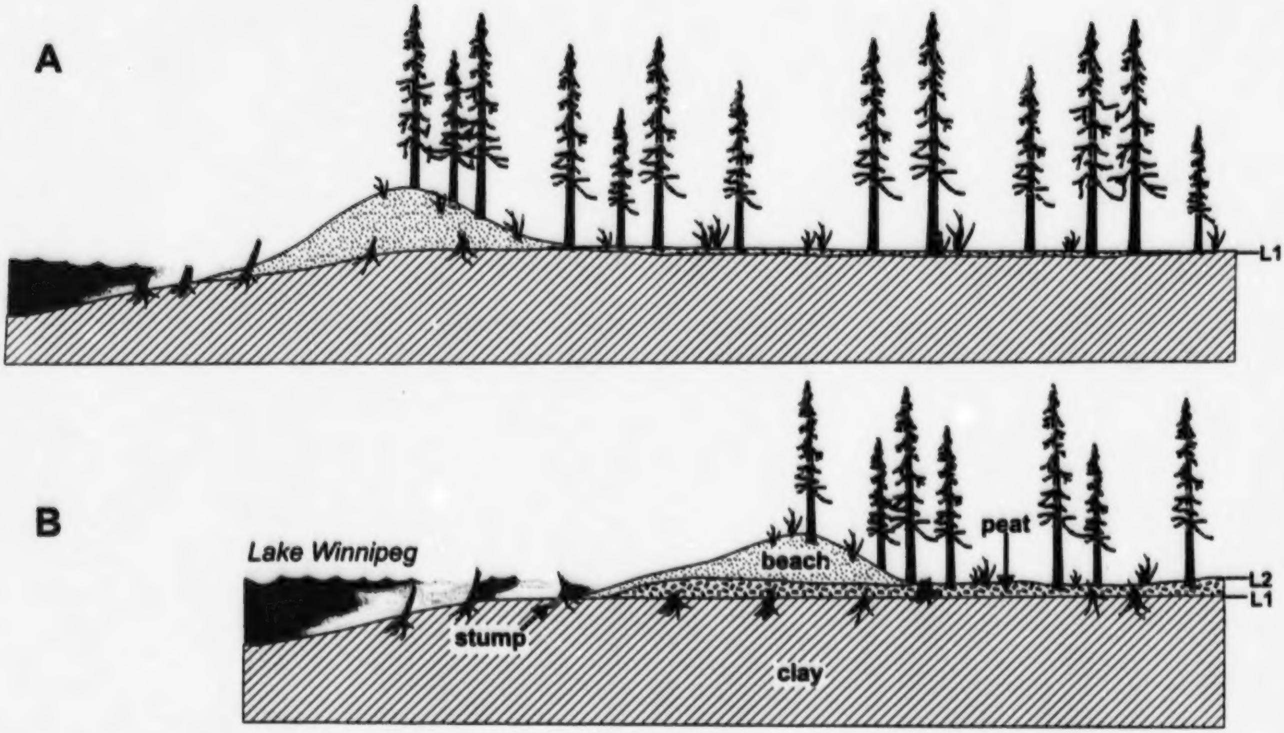
A
L1
B
Lake Winnipeg
beach
peat
L2
L1
stump
clay

Figure 2. Schematic model illustrating the origins of "drowned forests" on the foreshore of Lake Winnipeg by transgression into (A) a living forest, and (B) forested peat with previously dead *in situ* stumps and prone logs.

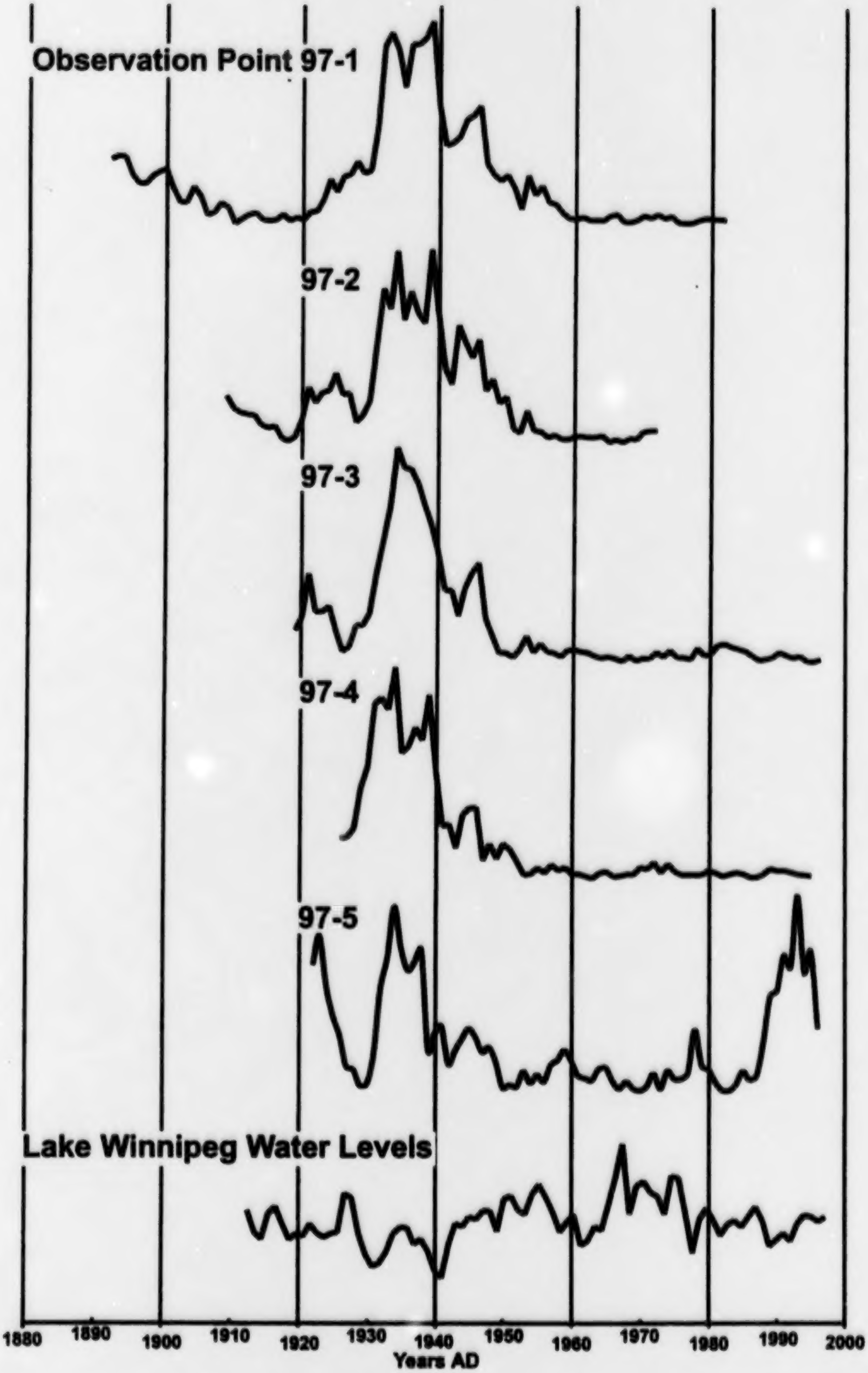

Figure 3. Tree ring curves for tamaracks at Observation Point and relative Lake Winnipeg water levels from 1913 to 1996.

9.2 Modeling wind-waves on Lake Winnipeg: an overview of the 1996 research program

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INTRODUCTION

An accurate description of a deep water or nearshore wave climate is fundamental to many aspects of ocean and coastal engineering; for example, the design of a drilling platform or breakwater, predicting alongshore currents or Lagrangian drift, or modeling sediment transport. However, it is not always cost effective or practical to deploy waverider equipment. Moreover, since long term statistics are often required for structural design, the "short-term" deployment of a waverider buoy would be of limited use. As a result, wave climates are often modeled using meteorological data.

Lake Winnipeg located in southern Manitoba is the 11th largest fresh water lake (by surface area) in the world. The southern basin of Lake Winnipeg, which is shown in figure 1, is quite shallow relative to its area (typically less than 10 m deep) and has very gentle nearshore slopes, i.e., on the order of 1:100. Lake Winnipeg also acts as a reservoir, with an operating range of 216.71 m to 217.93 m, for the operation of Manitoba Hydro's hydroelectric generating stations on the Churchill river.

As a first step to better understanding wind-wave driven processes on Lake Winnipeg, a research program was established to collect the data necessary to calibrate and test a model to predict the wave climate.

THE 1996 FIELD EXPERIMENT

During the summer of 1996 the Lake Winnipeg shore processes program was undertaken in collaboration with Drs. Forbes (Geological Survey of Canada Atlantic), Thorleifsen (Geological Survey of Canada Ottawa), and Nielsen (Manitoba Energy and Mines). The wave modeling component of this program involved the deployment of a north-south array of three waverider buoys in the southern basin of Lake Winnipeg (Fig. 1).

A north-south arrangement of waverider buoys was chosen because storm winds over Lake Winnipeg tend to originate from a northerly direction. The synoptic array of waveriders allow a comparison of predicted and observed wave conditions, as well as examining wave growth (at least to the extent that the frequency response of the buoys allow).

PRELIMINARY ANALYSIS OF DATA

Meteorological data

Over water meteorological data (wind speed, direction and maximum gust, water and air temperature, and barometric pressure) were obtained from the Environment Canada buoy located at 50°47' N and 96° 44' W, approximately one watch circle for the northern nondirectional buoy (Fig. 1). The buoy recorded hourly almost continuously from June 24 to July 13 and July 22 to October 2. A maximum wind speed reading of 50.4 km/h bearing 140° occurred on September 5. Hourly wind speed and direction recorded from June 12 to October 27 were also obtained for Gimli and Victoria Beach, located on the west and east shores of the south basin, respectively; the data from these locations will be used to examine the spatial variation of atmospheric conditions. A maximum wind speed of 61 km/h bearing 340° occurred at Victoria Beach on October 17 at 2200 GMT and 50 km/h bearing 340° at Gimli on October 17 at 2000 GMT. The meteorological data for Gimli, Victoria Beach and the meteorological buoy collected in the Summer of 1996, by Environment Canada are presented in Figures 2-4. The graphs on the left side show wind direction in degrees plotted against Julian day. The graphs on the rights side show wind speed in km/h plotted against Julian day.

The meteorological data were analyzed to find days where wind speed readings in excess of 30 km/h and 40 km/h occurred . This analysis was primarily preformed to identify the energetic days. The results of this analysis found that for the meteorological buoy 13 days had wind speed readings over 40 km/h and 55 days had wind speeds over 30 km/h. For the Gimli station it was found that 9 days had wind speeds over 40 km/h and 41 days had wind speeds exceeding 30 km/h. For the Victoria Beach station it was found that 34 days had wind speeds readings that were in excess of 40 km/h and 65 days with reading exceeding 30 km/h.

Waverider data

The north-south array of waverider buoys consisted of two nondirectional (0.7 m) Datawell Waveriders and one directional (0.9 m) Datawell WAREC. The northern nondirectional buoy was located at 50° 45' N and 96° 45' W, the southern buoy at 50° 31' 8" N and 96° 45' W and the directional buoy at 50° 38' 4" N and 96° 45' W. The nondirectional buoys were deployed from June 13 to October 27, inclusive; several weeks are missing from the north buoy due to technical difficulties. The directional buoy was deployed September 13 to October 27, inclusive. Each buoy transmitted to a shore-based station located at Grand Beach where the signal was sampled and logged (almost continuously) for the entire deployment period. The nondirectional buoys were sampled at 5 Hz while the directional buoy was sampled at 1.28 Hz.

A sample time series and spectrum for the most energetic day, October 17 2300 GMT is shown in Figure 5. The top figure shows a sample time series of heave. The bottom figure shows a sample spectrum. The significant wave height (calculated using the zero up crossing method) and peak period for this time series are 1.83 m and 4.56 s, respectively. Significant wave heights and peak periods were calculated and plotted for all the data for each of the three waveriders and are presented in Figures 6-8. The directional components of pitch and roll from the directional waverider have not been included.

Developing a wave prediction model for Lake Winnipeg

These data will be used to develop a wave prediction model for Lake Winnipeg. The SWAN model developed by Holthuijsen et al. (1993) appears well-suited to the present application. The authors have provided source code so that the model may be adapted (calibrated) to the present application. The SWAN model will be used to model the wave heights from the north to south end of the south basin. The three waverider buoys provide spot measurements of wave conditions to which the SWAN model may be calibrated.

Over water meteorological measurements will also be used to examine (and remove if necessary (Bishop et al., 1989)) the influence of atmospheric stability on wave growth (following Donelan et al.,1992). Meteorological data will be used to predict deep water wave height, periods and direction; the method proposed by Donelan et al. (1985) will be employed. A PHEW (Parametric Hindcasting of Effective Waves) type model (Fleming et al., 1984) developed for a previous Lake Winnipeg project, based on the wave, height, period, and direction model proposed by Donelan et al. (1985) will also be used to predict deep water conditions.

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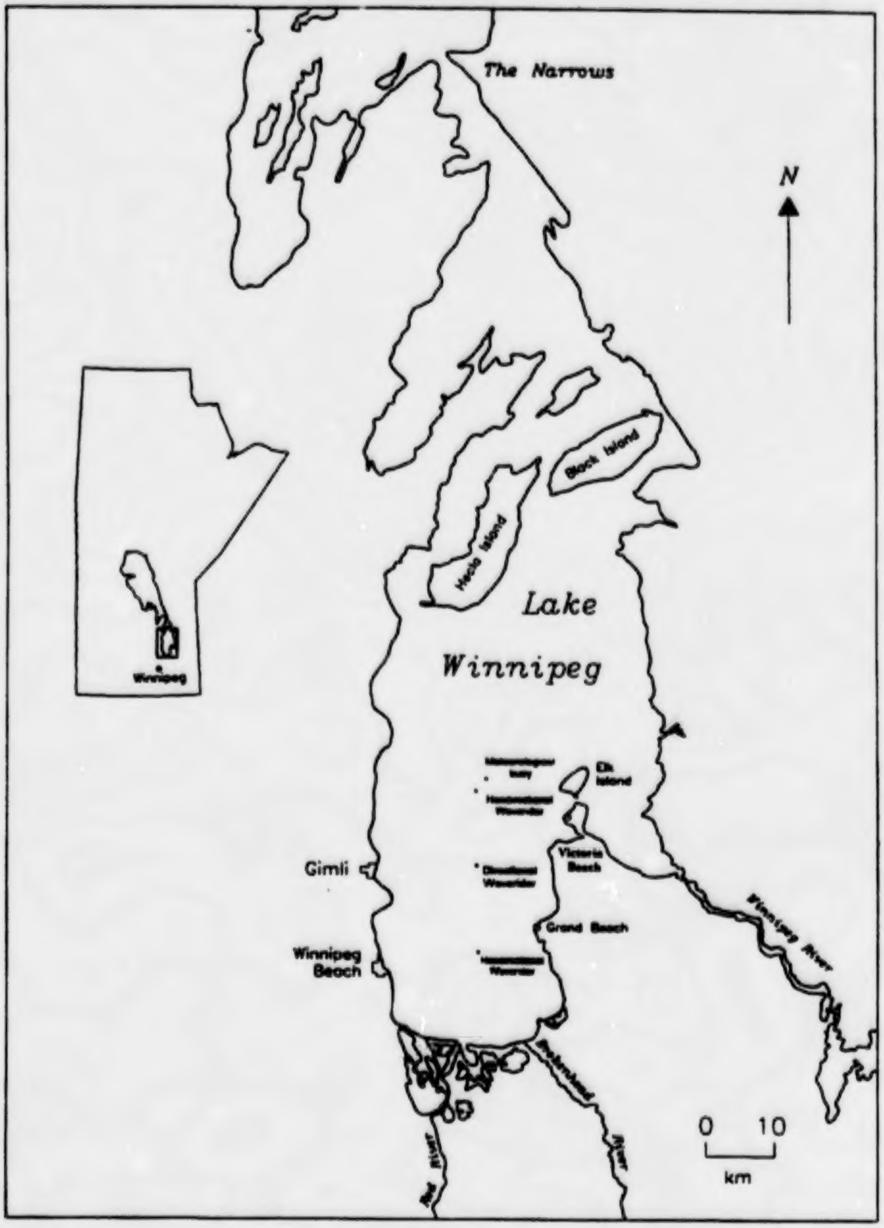

The Narrows
N
Black Island
Hecla Island
Lake
Winnipeg
Winnipeg
Elk Island
Victoria Beach
Gimli
Grand Beach
Winnipeg Beach
Winnipeg River
Red River
Brokenhead River
0 10
km

Figure 1. The southern basin of Lake Winnipeg.

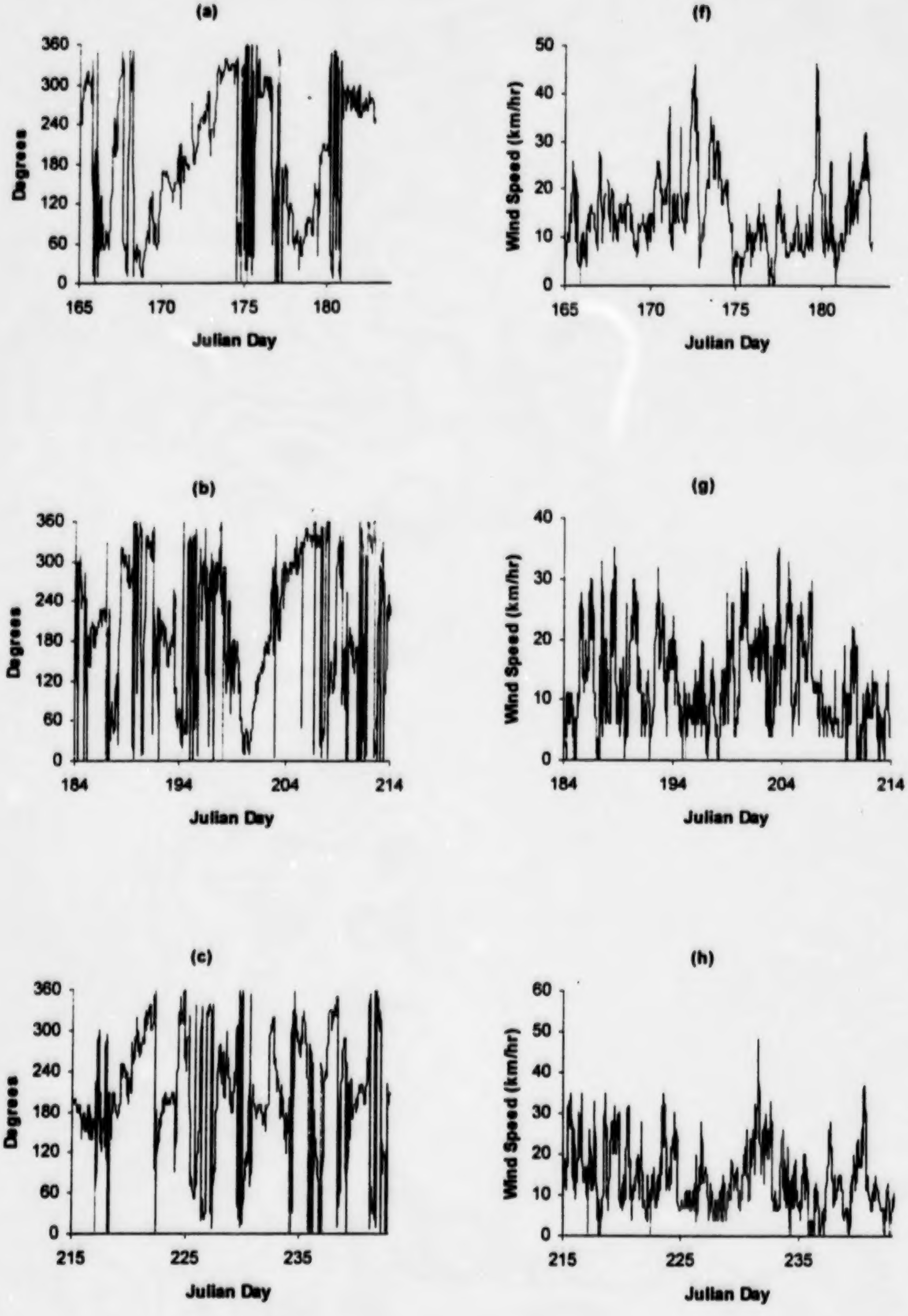


Figure 2. Summary of Gimli wind direction (a-e) and wind speed (f-j).

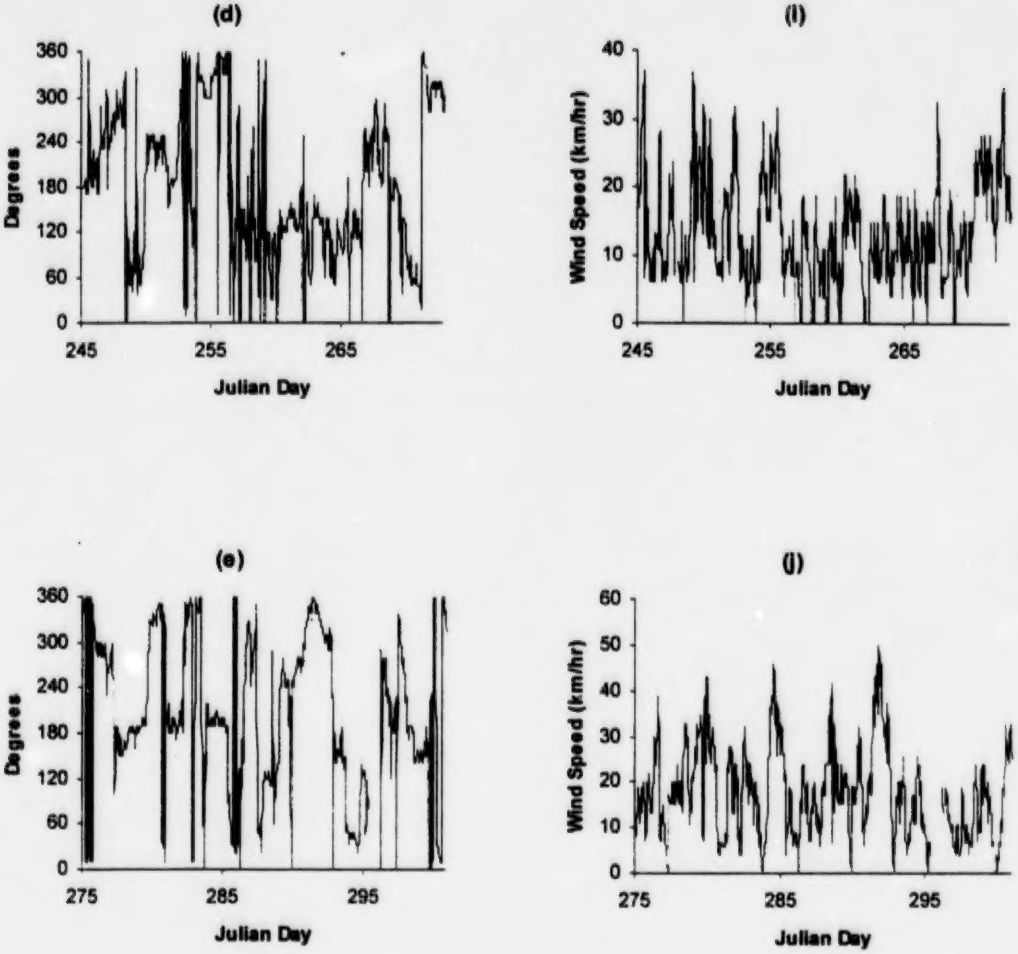


Figure 2 cont'd. Summary of Gimli wind direction (a-e) and wind speed (f-j).

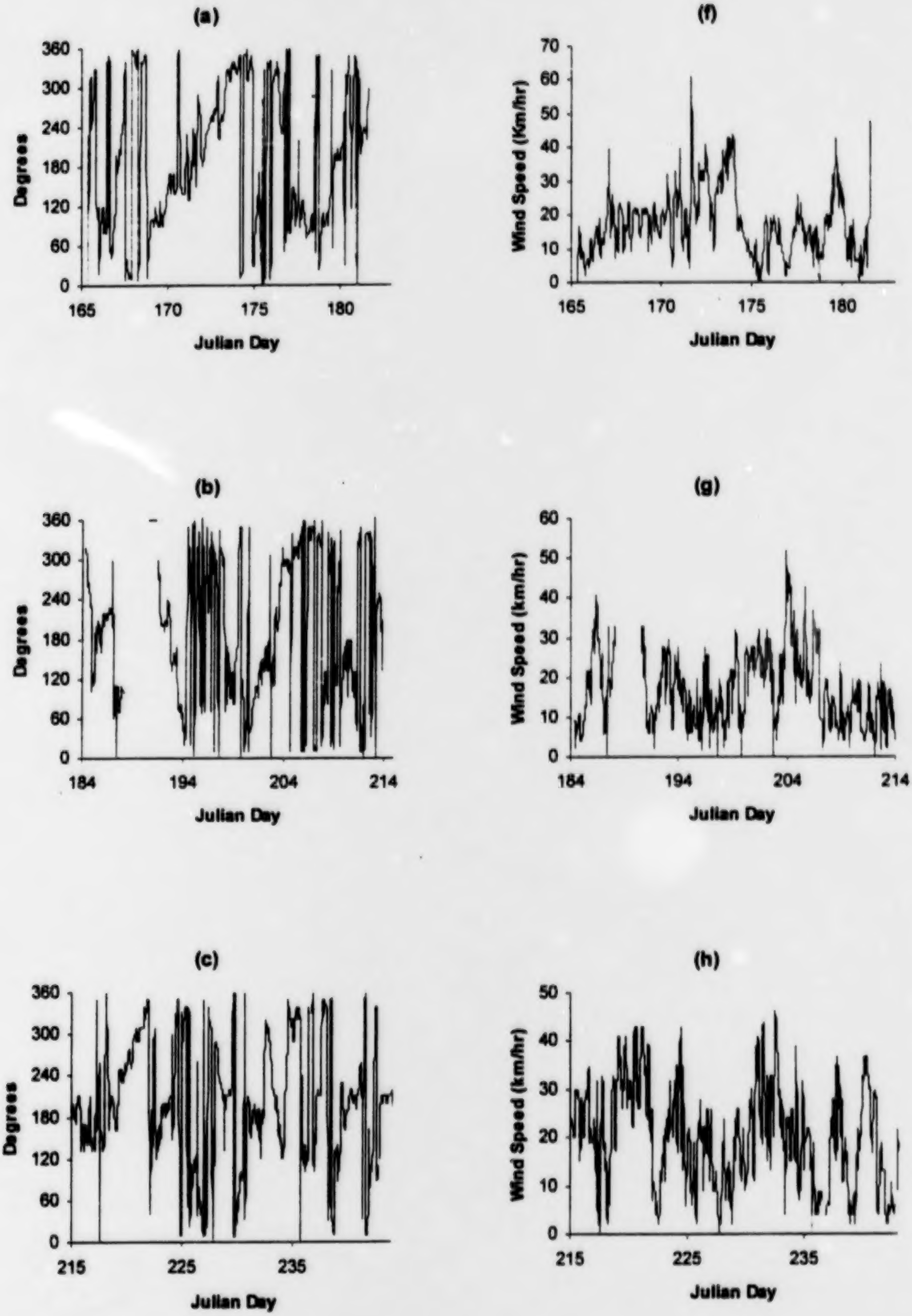


Figure 3. Summary of Victoria Beach wind direction (a-e) and wind speed (f-j).

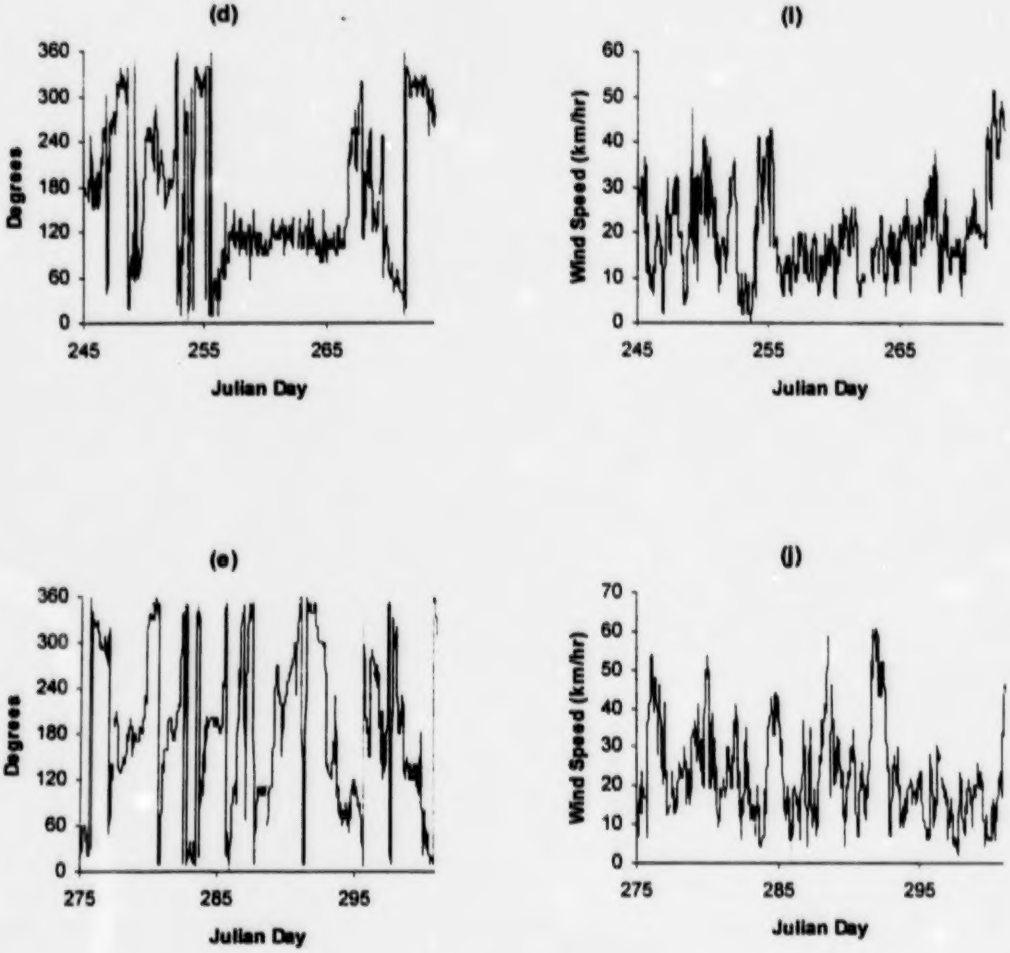


Figure 3 cont'd. Summary of Victoria Beach wind direction (a-e) and wind speed (f-j).

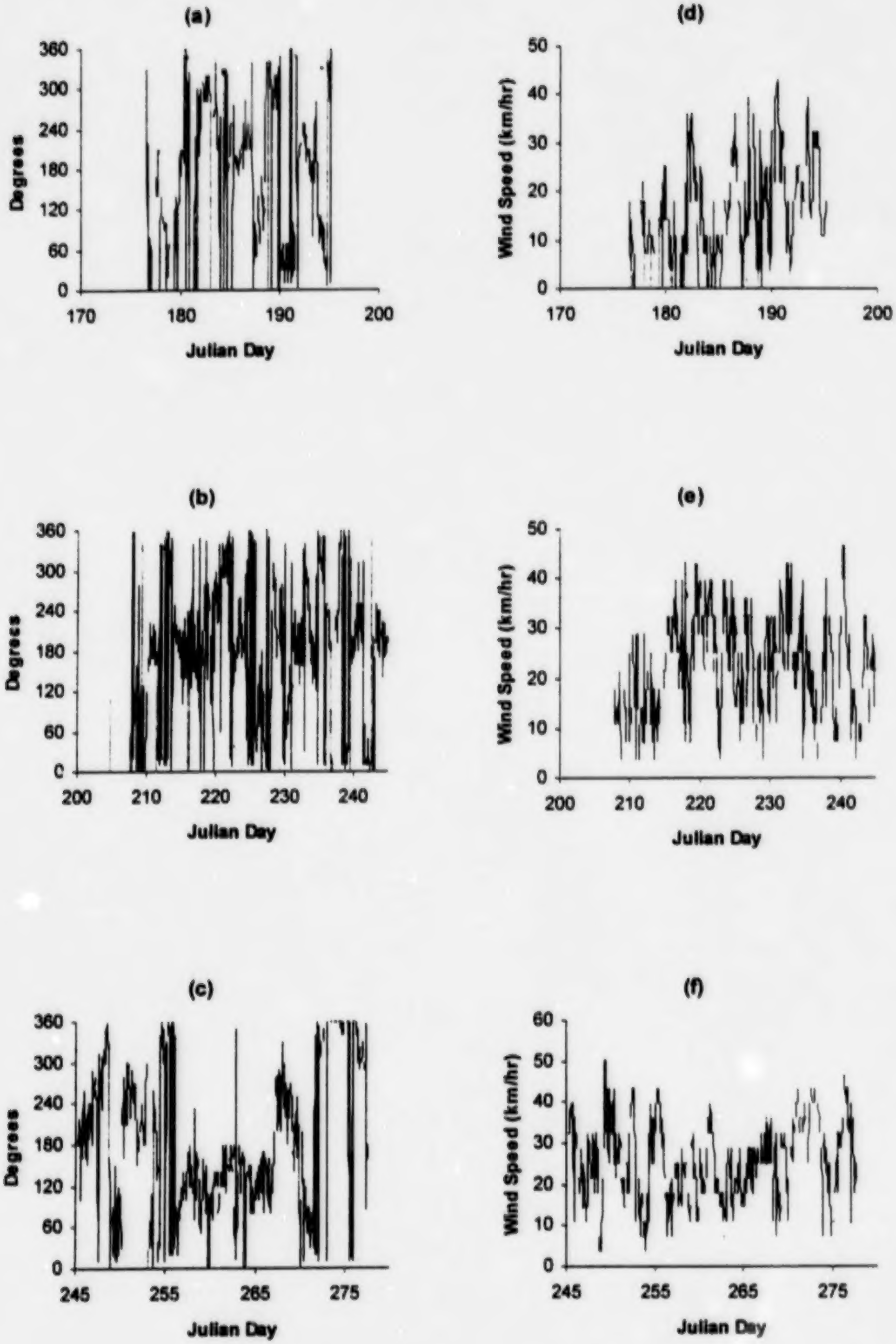


Figure 4. Summary of meteorological buoy wind direction (a-c) and wind speed (d-f).

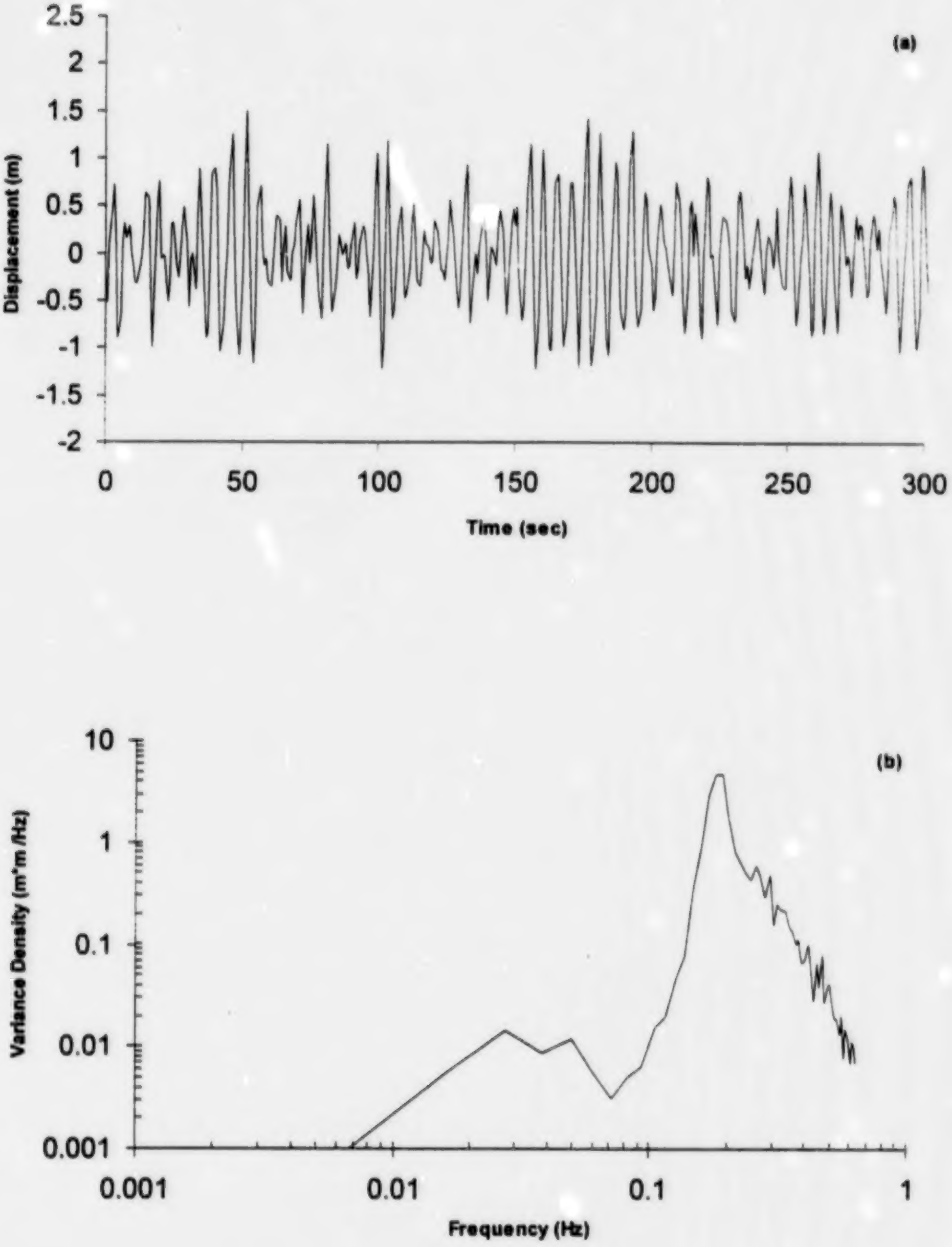
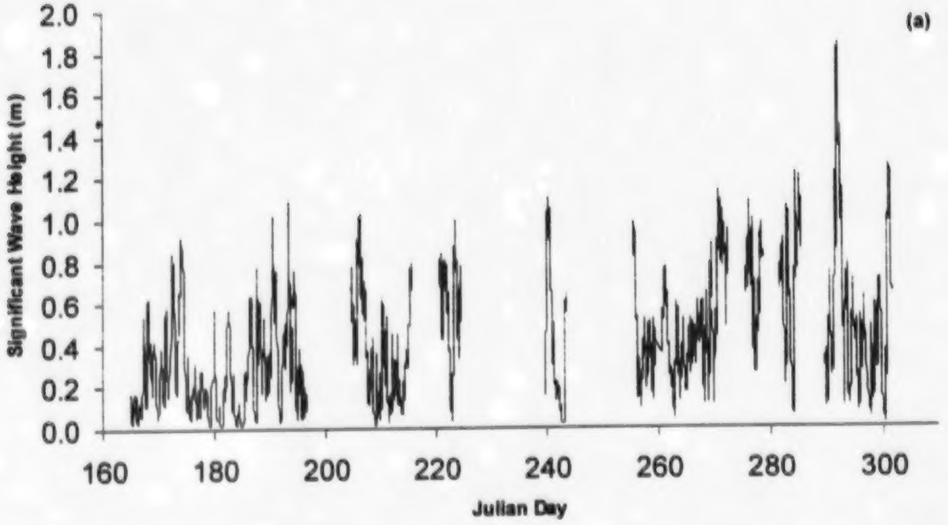


Figure 5. Sample time series (a) and spectrum (b) from directional buoy for October 17/96 2300.



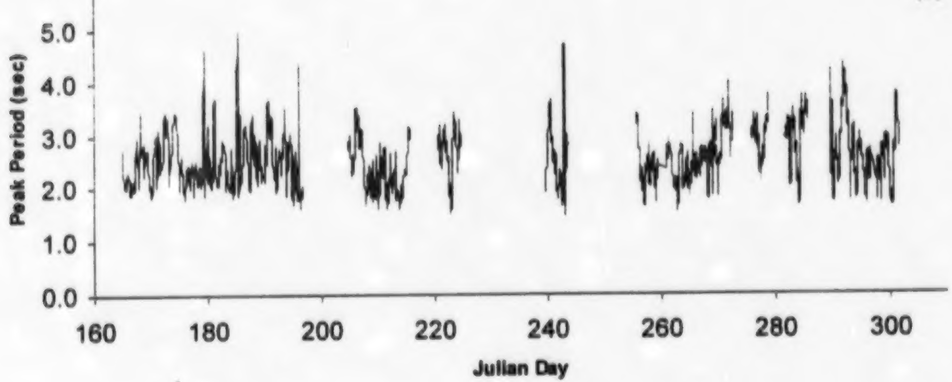


Figure 6. North buoy significant wave heights and peak periods versus Julian day. The missing portion of the data are due to wave buoy transmission/receiver problems.

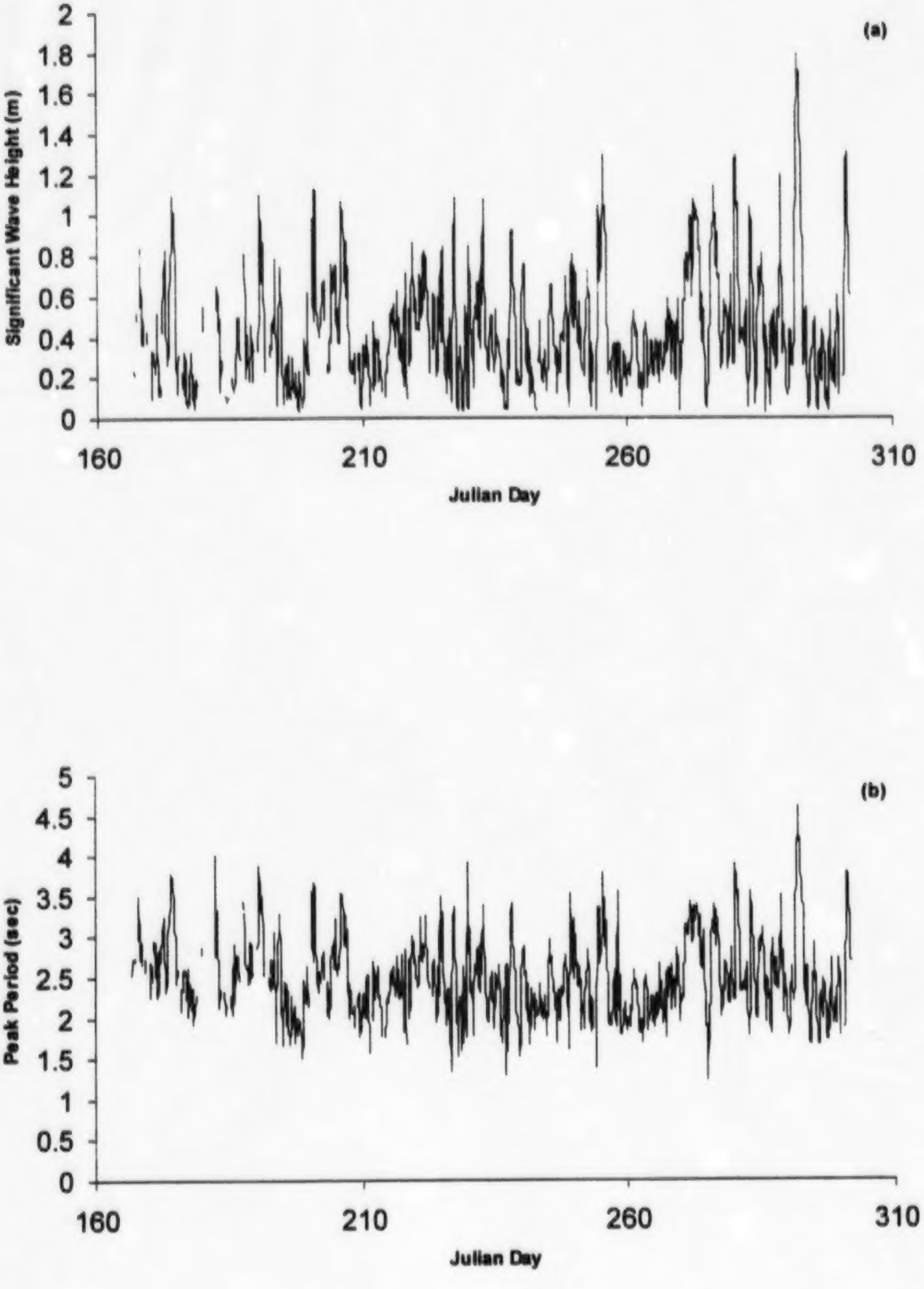


Figure 7. South buoy significant wave heights and peak periods versus Julian day.

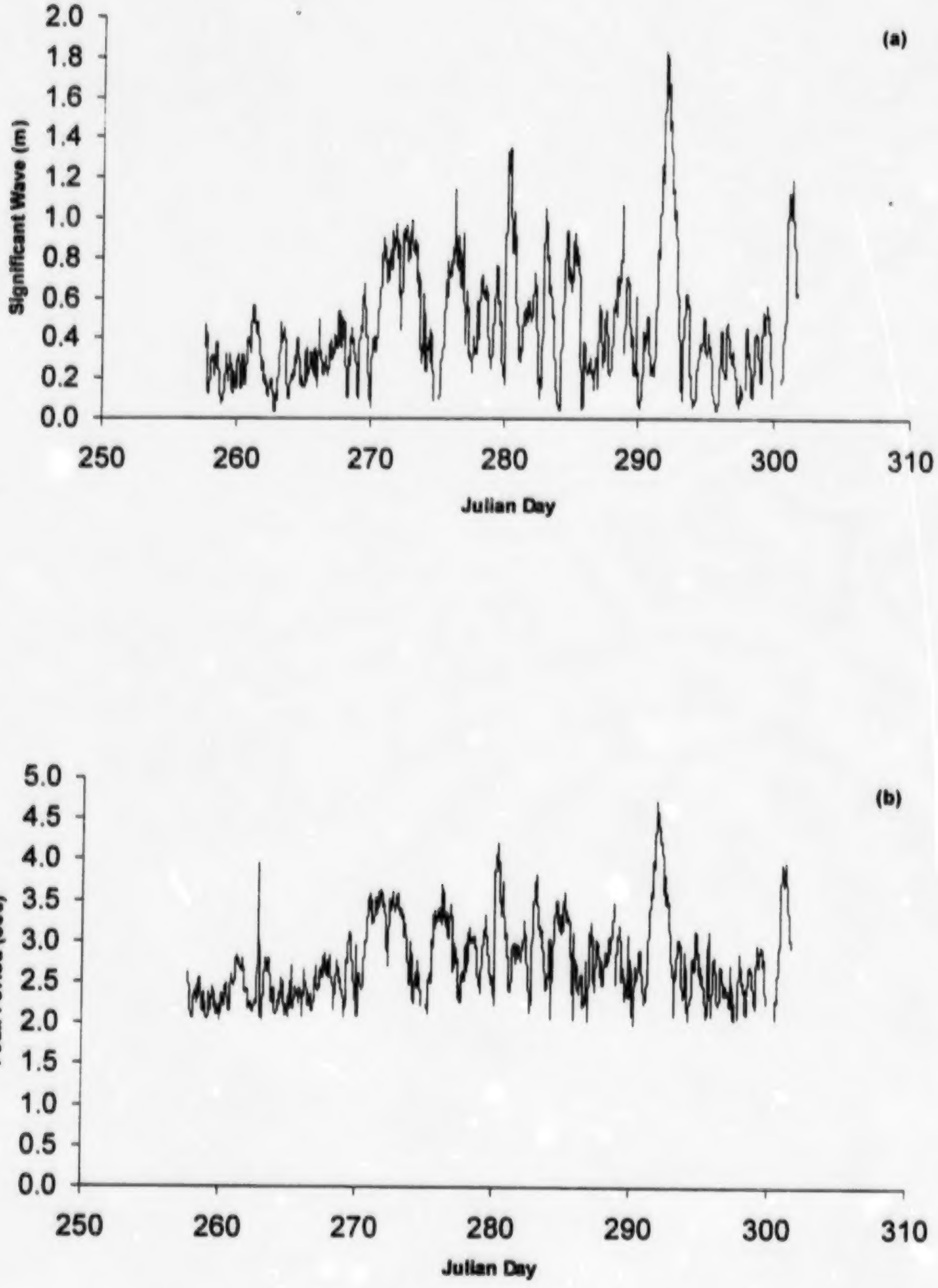


Figure 8. Directional buoy significant wave heights and peak periods versus Julian day.

9.3 Crustal movement: Measurement and prediction

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ABSTRACT

Facilities for repeated measurement of position and gravity have now been established along a roughly north-south transect across the Nelson and Churchill River drainage basins. High-precision data are being recorded at seven stations along the transect for the purpose of measuring present-day postglacial rebound. The intention is to combine these geodetic data with geomorphological data on late-Holocene vertical crustal movements to produce a best estimate of present and recent tilt rate and direction in this area. An improved tilt model in Manitoba is expected to influence Lake Winnipeg reconstructions and forecasts of shoreline inundation. A preliminary attempt to combine presently-available absolute gravity data at Churchill over an eight-year time span with Lake Agassiz strandline tilt data from southern Manitoba indicates disagreement with existing models. This shows the need for improved numerical reconstructions of ice-sheet history in the region. A comparison of theoretical results for two different ice-sheet histories at the present project sites shows the resolving power of sampling at geodetic sites running from near maximum uplift to maximum peripheral subsidence.

INTRODUCTION

Present-day postglacial rebound rates in central North America are now being measured using continuous Global Positioning System (GPS) measurements and repeated absolute gravity measurements at a small number of stations (Fig.1). The five-year project which started in 1996 is a co-operative project supported by GSC, Manitoba Hydro, NASA, NOAA, and Geomatics Canada. The objective of the project is to substantially improve estimates of the present-day crustal tilt rate throughout the Nelson and Churchill River drainage basins, including Lake Winnipeg and its tributaries. The water-level history, future outflow capacity and shoreline configuration of Lake Winnipeg and its subsidiary basins depend to a large extent on the past and present vertical movement of certain critical outlet points. An improved crustal tilt model will directly affect the question of reconstructing the water level history of Lake Winnipeg (Lewis and Todd, 1996; Lewis et al., this volume). The new combined regional data is also expected to contribute substantially to development of a more-realistic, general model of the Laurentide ice sheet and a better determination of the rheological properties of the Earth.

For the first time geodetic estimates of present-day crustal movement along a transect cutting directly through the drainage basin will be combined with late-Holocene geological data from the region. This report gives the status of the geodetic measurement component of the project up to Spring 1997.

FIELD MEASUREMENTS

Two continuously-operating GPS receivers were established at Flin Flon and Pinawa, Manitoba in June and October 1996, respectively. The GPS receivers, ROGUE SNR-8000's, were obtained on long-term loan from NASA under the Solid Earth and Natural Hazards Program. Construction of GPS buildings and antenna monuments and installation of data communication equipment and un-interruptible power supplies were carried out by GSC with funding from Manitoba Hydro. Data from these two stations are transmitted every four hours by automatic telephone dial-up to Pacific Geoscience Centre (PGC), Geological Survey of Canada - Pacific in Sidney, British Columbia. The data are preprocessed and archived at PGC and also acquired by Geomatics Canada (Geodetic Survey), reformatted and retransmitted to the NASA Crustal Dynamics Data Information System. It is intended that these GPS receivers will be operated at these stations for a period of five years in conjunction with existing GPS receivers at Churchill and Iowa City (North Liberty), Iowa (Table 2). Analysis of daily baselines among the four mid-continent stations and other selected GPS receivers in Canada and the USA will be carried out to determine the relative vertical and horizontal crustal velocities for comparison with theoretical model predictions. Churchill and North Liberty are stations participating in the International GPS Service for Geodynamics (IGS).

A new type of high-stability GPS antenna monument was jointly designed by GSC and Geomatics Canada (Geodetic Survey Division) with engineering assistance from Canada Centre for Mineral and Energy Technology. The new monument was constructed at the Flin Flon station and is designed to be stable vertically to better than one millimetre over a temperature range of 60° C. It features a central invar rod anchored in bedrock 3m below the surface, high-stability concrete and non-ferrous reinforcing. The central invar rod feature was copied from a GPS monument constructed in Greenland (J. Wahr and T. vanDam, personal communication).

Absolute gravity measurements have been carried out by GSC and NOAA at all seven project sites (Fig. 1) in 1995 and 1996 using FG5 model absolute gravimeters. Table 2 summarizes the observations carried out to-date. By the end of the 1997 field season we expect to be able to make the first preliminary estimates of gravity change rates at all stations. As shown in the table Churchill and International Falls have each been occupied for several years, although the data for the early years are less precise than the last two years. Result for Churchill are summarized below.

It has become better appreciated recently that the vertical gravity gradient at many sites departs significantly from linearity. This becomes a significant factor when measurements made by different instruments at different heights are reduced to the standard international height of 1m. Consequently, the vertical gravity gradients at Churchill, Flin Flon, Pinawa, Int. Falls, Wausau and Iowa City were remeasured. The measurements were carried out using a LaCoste and Romberg model-D gravimeter (D-06) and a three-level tripod. At least seven vertical ties were measured between each of the three levels (AB,BC,CA) and a least-squares adjustment of the data was made. Interpolation between measurement heights was done through a theoretical model of the expected gravity variation above each station marker. The new vertical gravity profiles should keep the vertical transfer uncertainty to less than 1 μGal (the precision of the absolute measurements themselves).

Care has been taken to ensure that no unexpected biases arise in the Canadian FG5-106 gravimeter with respect to the USA FG5-102 instrument. Measurements are made every year by the Canadian FG5-106 instrument at the Table Mountain Geophysical Observatory near Boulder, Colorado prior to each measurement campaign on the mid-continent line. Table Mountain Geophysical Observatory is the home base for the USA FG5-102 instrument.

Related work on identification and measurement of proglacial Lake Agassiz strandlines in central Manitoba continued during 1996-97 (L.H. Thorleifson, pers. comm, 1997).

RESULTS TO DATE

Geodetic data of the type described above (present-day vertical and horizontal velocities and rates of change of gravity) can be used to constrain postglacial rebound models consisting of a Laurentide ice-sheet model combined with a model of the rheological properties of the "solid" earth (James and Lambert, 1993). Geomorphological data on the net tilting of proglacial lake shorelines since they were formed can also be used to constrain the same ice-sheet/earth rheology model. We believe there is a great deal to be gained from an understanding of how the different features of the model are constrained by the different types of data available.

Two available data sets representing paleo-geomorphological and geodetic data types, respectively, are 1) tilting of the 9.5 kyr B.P. Campbell strand line south and west of Lake Winnipeg, and 2) the rate of decrease in absolute gravity values measured from 1987 to 1995 at Churchill, Manitoba (Fig. 4). These data have been compared (Lambert et al., 1998) to theoretical predictions based on the published ICE-3G loading history and on a model of Earth rheology characterized by a 1066B elastic structure, an upper-mantle viscosity of 10^{21} Pa s, a lower-mantle viscosity of $2x10^{21}$ Pa s, and a lithosphere thickness of 120 km (Tushingham and Peltier, 1991). This "standard" model predicts significantly more tilt than the observed tilt of the Campbell strand line, whereas it predicts a significantly lower rate of decrease of gravity at Churchill than is observed. By varying key parameters of the model we show that, taken together, these data are consistent with 1) a thinning of the Laurentide ice-sheet over the Prairies relative to the ICE-3G model, and 2) a higher lower mantle viscosity relative to the Earth rheology assumed in the development of ICE-3G. The present data do not appear to constrain lithosphere thickness very well. A new model, ICE-4G (Peltier, 1994) fits the gravity change data better than the earlier ICE-3G model. Simultaneous adjustment of model parameters with the advantage of anticipated new data in Manitoba and adjacent regions in the USA will lead to better understanding of the trade-offs between earth rheology and ice sheet history and hence to an improved Laurentide postglacial rebound model.

DISCUSSION

The GPS and absolute gravity data now being collected at stations south of Churchill are expected to provide rates of change accurate enough to constrain postglacial rebound models significantly better than present modelling uncertainties by 2001. The precision of a measurement of rate of change of height or rate of change of gravity can be estimated knowing the precision and frequency of the individual measurements of height and gravity (Lambert et al., 1989). The principal assumption is that the errors on the measurements of height and gravity are 10 mm and 2 μGal, respectively and that the errors on these measurements are normally-distributed, random errors. On the basis of this statistical analysis, the daily GPS measurements are expected to yield a rate of change in height with a standard error of 1 mm/yr well within the five year time frame. The absolute gravity measurements are expected to yield a rate of change of gravity with a standard error of 0.3 μGal in five years. To put this in perspective, the standard error on the height rate determination is 10% of the expected maximum rate (at Churchill) and the standard error on the gravity rate is 20% of the expected maximum rate. This is mainly due to the fact that gravity is measured less frequently.

The ratio of the rate of change of gravity to the rate of change of height varies significantly from one process to another. For postglacial rebound the ratio is predicted by theoretical models to be about -0.15 μGal/mm. The role of repeated absolute gravity measurements is to verify that the vertical movement detected by the GPS measurements is the result of postglacial rebound and that the observed GPS rates are not contaminated by unexpected biases. If the GPS and absolute gravity measurements are shown to be consistent with theory, absolute gravity measurements may be used as a proxy for height change observations.

Table 4 compares present-day predicted rates of change of vertical and horizontal position and gravity for the "standard" ICE-3G model and an "iterated" model having thinner ice over the Prairies. We see clearly that, while the rate of change of height and gravity at Churchill is not very different for the two models, there is a marked difference as we go south. For the ICE-3G model the change from uplift to subsidence occurs somewhere between International Falls (USA border) and Wausau, Wisconsin (See Fig.1) while for the "iterated" model the zero line has shifted north to lie between Lac du Bonnet (Pinawa) and Flin Flon, Manitoba. The height rate differences between the two models in the vicinity of the zero line are around 2.5 mm/yr and, therefore, should be resolvable at the individual stations by GPS measurements. The corresponding rate difference in gravity is smaller compared to the precision of the rate estimates but should be resolvable over the five year period by combining measurements at two or more stations.

ACKNOWLEDGEMENTS

The success of the project described above depends on the co-operation and support of a large number of individuals and agencies in Canada and the USA. We thank Glenn Sasagawa, Fred Klopping, Dan Winester and Jaques Liard for supporting this project with state-of-the-art absolute gravity measurements. We are grateful to Herb Dragert and Mike Schmidt for their unflagging support in the design and operation of the Flin Flon and Lac du Bonnet GPS stations and to personnel of Geomatics Canada for assistance with data dissemination and archiving. The GPS receivers installed at these stations are on loan from the USA National Aeronautics and Space Administration under the auspices of the Solid Earth and Natural Hazards Program. Manitoba Hydro is providing all ancillary GPS equipment and data communications at these stations. Engineering support and materials from Canada Centre for Mineral and Energy Technology for a new GPS antenna design is gratefully acknowledged. Sites for GPS operations in Flin Flon and Lac du Bonnet are provided by the Canadian Department of National Defence and Atomic Energy of Canada Ltd., respectively. Absolute gravity observations are carried out jointly by Geological Survey of Canada and the USA National Oceanic and Atmospheric Administration. Last but not least we acknowledge the critical support of Harvey Thorleifson, GSC, and Randy Raban, Manitoba Hydro, in recognizing the potential of geodetic methods in the study of crustal tilting and its environmental effects in Manitoba.

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Table 1. Measurement status of mid-continent geodetic stations to date.

Station Name	N. Lat.	E. Long.	Station Type	Measurement Status
Churchill, Man.	58.76	265.91	GPS Repeat abs.-g	Continuous (Geodetic Survey) 8 occup.(GSC); 5 occup.(NOAA)
Thompson, Man.	55.83	262.03	Repeat abs.-g	1 occup.(GSC); 2 occup.(NOAA)
Flin Flon, Man.	54.72	258.02	GPS Repeat abs.-g	Continuous (GSC) 2 occup.(GSC); 2 occup.(NOAA)
Pinawa / Lac du Bonnet, Man.	50.27	265.12	GPS Repeat abs.-g	Continuous (GSC) 4 occup.(GSC); 1 occup. (NOAA)
International Falls, Min.	48.58	266.83	Repeat abs.-g	1 occup.(GSC); 8 occup.(NOAA)
Wausau, Wisc.	44.92	270.32	Repeat abs.-g	2 occup.(GSC); 1 occup.(NOAA)
North Liberty / Iowa City, Iowa	41.35	266.65	GPS Repeat abs.-g	Continuous (NASA/JPL) 2 occup.(GSC); 1 occup.(NOAA)

Table 2. Mid-continent line continuously-operating GPS stations.

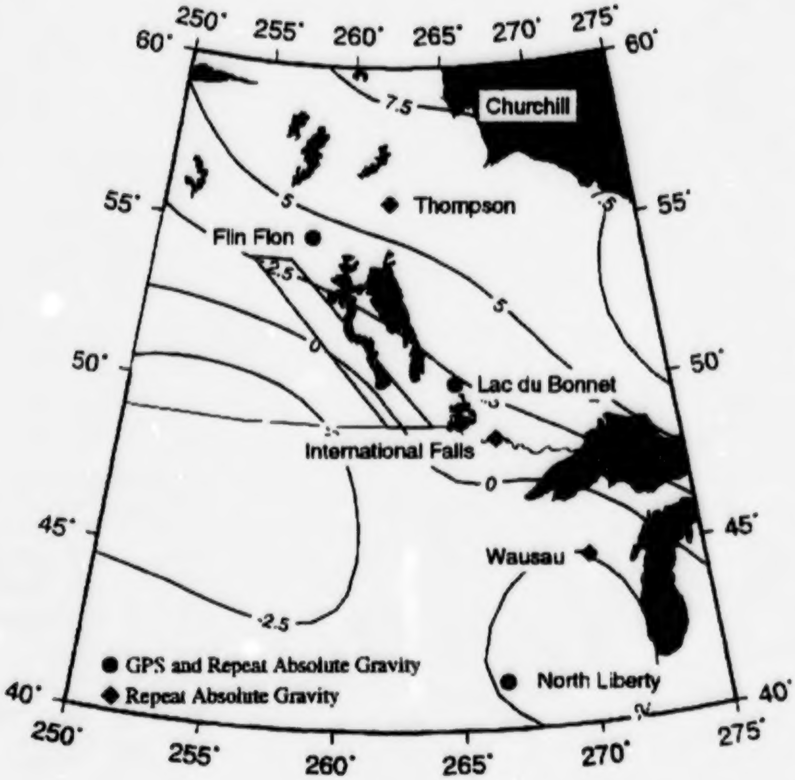
Station	N. Lat.	E. Long.	Receiver Type	Antenna Type	Date Installed	Data Collection
Churchill, Man.	58.76	265.91	ROGUE SNR-8000	DORNE MARGOLIN T	June 18 1996	Geodetic Survey Ottawa, Ont.
Flin Flon, Man.	54.72	258.02	ROGUE SNR-8000	DORNE MARGOLIN T	June 8 1996	GSC Sidney, B.C.
Lac du Bonnet, Man	50.27	265.12	ROGUE SNR-8000	DORNE MARGOLIN T	Oct. 18 1996	GSC Sidney, B.C.
North Liberty, Iowa	41.35	266.65	ROGUE SNR-8000	DORNE MARGOLIN T	Jan. 1 1996	NASA/JPL Pasadena, Cal.

Table 3. Mid-continent line absolute gravity measurements to date (GSC-○, NOAA-●).

Station	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Churchill	○	○	○		○	●	●	●	●○	●○
Thompson									●○	●
Flin Flon									●○	●○
Pinawa		○						○	●○	○
Int. Falls		●		●	●	○●	●	●	●○	○
Wausau									●○	○
Iowa City									●○	○

Table 4. Comparison of predicted crustal movement and gravity change rates for ICE-3G and an "iterated" Laurentide ice-sheet history.

Station	ICE-3G Model				"Iterated" Model			
	UP mm/yr	N mm/yr	E mm/yr	gdot µGal/yr	UP mm/yr	N mm/yr	E mm/yr	gdot µGal/yr
Churchill, Man.	7.58	-0.28	-0.02	-1.12	8.02	-0.45	-0.33	-1.19
Thompson, Man.	5.76	-0.50	-0.07	-0.85	3.73	-0.66	-0.53	-0.53
Flin Flon, Man.	4.23	-0.81	-0.24	-0.63	0.68	-0.67	-0.41	-0.06
Pinawa/Lac du Bonnet, Man.	2.29	-0.75	-0.39	-0.32	-0.27	-0.66	-0.52	0.08
Int. Falls, Min.	1.34	-0.87	-0.21	-0.18	-1.02	-0.61	-0.33	0.19
Wausau, Wisc.	-2.49	-0.77	-0.27	0.44	-2.98	-0.24	-0.16	0.50
N. Liberty/Iowa City, Iowa	-2.68	-0.12	0.18	0.42	-2.15	0.20	0.11	0.32



250°
255°
260°
265°
270°
275°
60°
55°
50°
45°
40°
Churchill
7.5
5
Thompson
Flin Flon
2.5
5
0
Lac du Bonnet
International Falls
0
Wausau
-2.5
North Liberty
● GPS and Repeat Absolute Gravity
◆ Repeat Absolute Gravity

Figure 1. Location of continuously operating GPS stations (dots) and repeat absolute gravity stations (diamonds). Repeat absolute gravity measurements are also made at the GPS stations. The GSC strand line study area in Manitoba is indicated by a quadrilateral. Contours are present-day uplift rates for the ICE-3G ice sheet model.

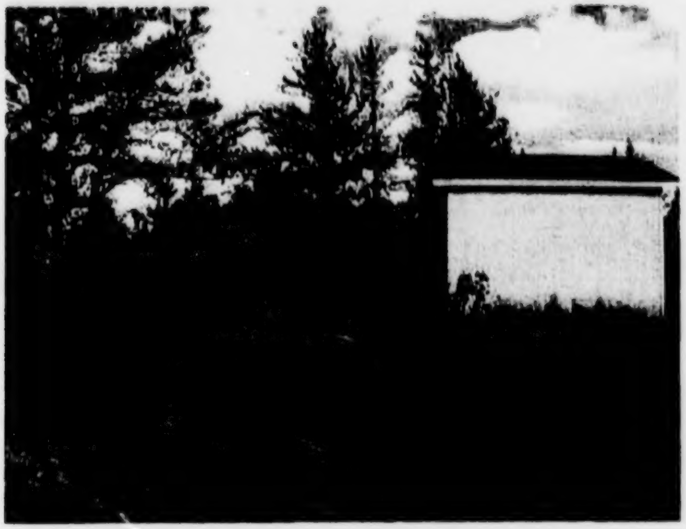


Figure 2a. Building dedicated to GPS and absolute gravimetry at the Underground Research Laboratory of the Atomic Energy of Canada Limited, Lac du Bonnet / Pinawa, Manitoba.

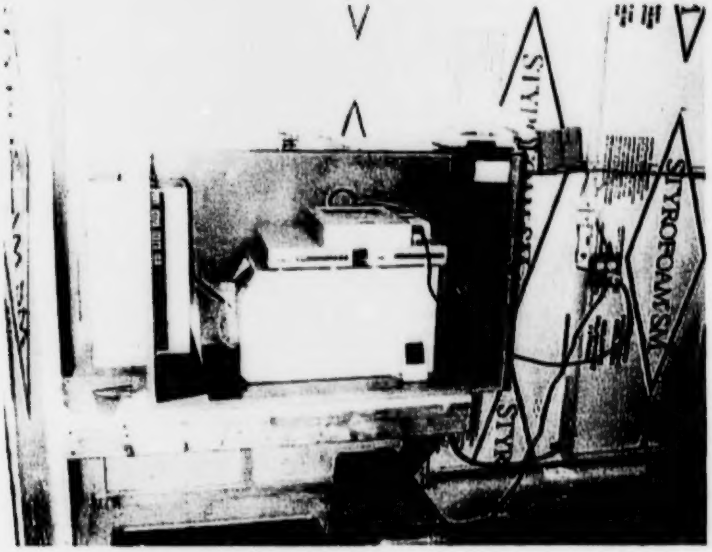


Figure 2b. GPS receiver set-up at Lac du Bonnet/Pinawa showing typical configuration of ROGUE receiver (small unit on top), telephone modems (2 middle units), uninterruptible power supply (larger bottom unit) and cooling/heating system (unit at left).

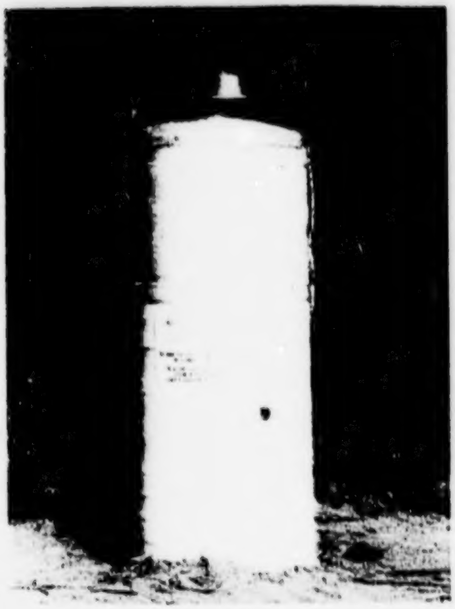


Figure 3a. High-stability GPS antenna monument at Flin Flon, Manitoba.

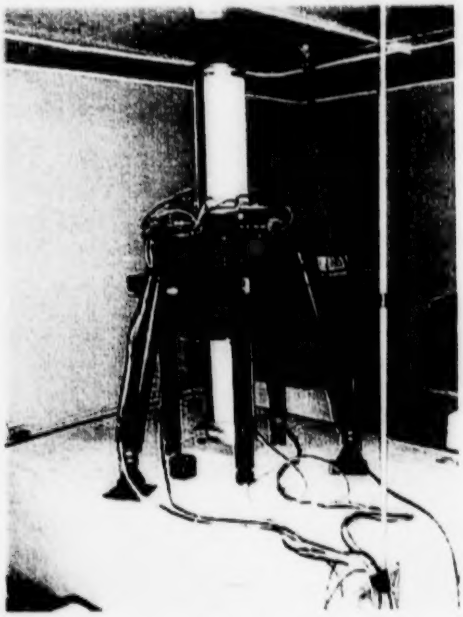


Figure 3b. The GSC's FG5-106 absolute gravimeter set up for a measurement at Churchill, Manitoba.

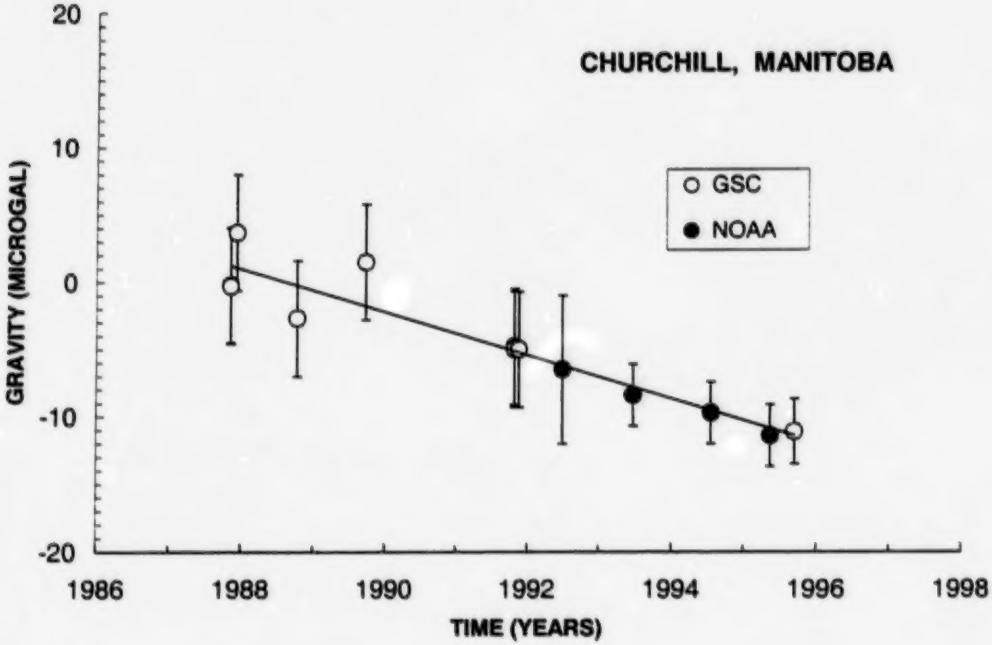


Figure 4. Plot of absolute gravity values from 1987 to 1995 at Churchill, Manitoba relative to a reference value of 981752820 μGal (9.81752820 m/s^2). The vertical bars denote the estimated 67% error level. Note the improvement in the precision of absolute gravity measurements in recent years.

9.4 Additional radiocarbon dates from the Minago River channel area

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ABSTRACT

Radiocarbon dates from basal limnic peat collected in the middle of the Minago River channel confirm that the diversion of the Saskatchewan River from the Minago channel to its present course eastward through Cedar Lake occurred in mid-Holocene time. The stratigraphic sequence in the core suggests major changes in depositional environments, from alluvial to shallow lacustrine at about 4.7 ka, which can be interpreted as channel abandonment, and from lacustrine to a sedge bog at 4.1 ka. No delay in the establishment of limnic peat forming vegetation is evident in the peatlands surrounding the Minago River channel, suggesting that the mid-Holocene radiocarbon age on limnic peat from the Minago River core is a reliable maximum age for channel abandonment.

INTRODUCTION

During the Ponton Phases of Glacial Lake Agassiz (circa 8000 years BP), the Saskatchewan River entered Lake Agassiz via the Minago River channel (Tarnocai, 1970; McMartin, 1996). After the final drainage of Lake Agassiz, the channel extended about 100 km, from Cedar Lake to Nelson River, bypassing Lake Winnipeg (Fig. 1). In mid-Holocene time, between 2.5 and 5.9 ka BP (McMartin, 1996), the Minago River channel was abandoned, perhaps as a result of uplift, and the Saskatchewan River was diverted to its present course, entering Lake Winnipeg at Grand Rapids. The flow diversion had a significant effect on Lake Winnipeg level (Lewis and Todd, 1996), as well as sedimentation in the Lake Winnipeg North Basin (Henderson, 1996). The objective of this short paper is to publish and comment on five new dates from peat and freshwater mollusk samples collected from a 2.5 m long core taken in the middle of the channel in July 1995.

MINAGO RIVER CORE

The Minago River core (site 95-0058) is located approximately 50 m west of Highway 6, about 1.2 km north of Minago River (54°13'N, 99°10'). In this area, the channel splits temporarily around a carbonate plateau into two arms of similar width and depth, to rejoin about 4 km to the east. The site is within the northern arm of the channel in a fen bog bordering the eastern shore of Wigle Lake. The top of the core is at 230 m elevation. The stratigraphy of the core consists of 3 units separated by sharp contacts (Fig. 2). Unit A consists of 223 cm of poorly to well decomposed woody peat, largely derived from sedges. Unit B consists of 17 cm of limnic peat and can be separated into two sub-units, the top unit B1, composed of dark brown organic limnic sediments, and the underlying B2, similar to B1 in composition but with small mollusk shells enclosed. Unit C is composed of grey, calcareous (20% $CaCO_3$), sandy silts, with small mollusks and aquatic organic fragments. This unit is continuous in the channel between Moon Lake and Hill Lake (McMartin, 1993), and is also abundant in the present-day floodplain and abandoned channels of Saskatchewan River (McMartin, 1997; McMartin and Boucher, 1995; McMartin et al., 1995). Mollusks in both unit C and B2 include mainly gastropods (aquatic snails) with minor pelecypods (bivalves). At least 8 species of gastropods (predominantly *Gyraulus* sp., *Valvata* sp.) and 2 species of pelecypods (predominantly *Pisidium* sp.) have been identified (J-M. Gagnon, Canadian Museum of Nature). Today, these mollusks occur in shallow lakes and slow-moving waters on muddy bottoms among aquatic vegetation (Clarke, 1981). The top of Unit C is therefore interpreted as alluvium deposited by slow-moving waters of Saskatchewan River before the final abandonment of the channel.

POLLEN STRATIGRAPHY

A pollen diagram encompassing the depth interval 205-242 cm, which covers the major stratigraphic breaks, shows moderate to high percentages of tree and shrub pollen notably *Betula* (birch), *Picea* (spruce), *Pinus* (mainly jack pine) and *Alnus* (green and speckled alder), typical of modern-day boreal forest (Fig. 3). Presence of *Alnus* (alder), willow and *Typha* (cat-tail) pollen in combination with the aquatics *Pediastrum* (algae) and *Myriophyllum* (water-milfoil) suggest the site resembled an alder-willow-reed-bordered shallow lake during the deposition of units B2 and B1 (T. Anderson, pers.comm.). With time, the pond became infilled and was transformed into a sedge bog during deposition of

Unit A, judging by the upward decrease of *Typha* and increase of Cyperaceae. A good correlation between the pollen diagram and the basal portion of a pollen diagram from near Grand Rapids (Ritchie and Hadden, 1975) suggests that the Minago River channel sediments (195-250 cm depth) commenced deposition during the middle Holocene.

RESULTS AND DISCUSSION

The radiocarbon ages obtained from the Minago River core and two additional dates from sites located in the channel are reported in Table 1. The oldest radiocarbon age in the core was obtained from mollusks enclosed in the bottom alluvial silts at 5210 ± 60 yr BP (TO-5700). This date is likely too old, due to the hard-water effect from the calcareous sediments of the Saskatchewan River. Based on the comparison between an AMS ^{14}C age of 4880 ± 60 yr BP (TO-5699) obtained from mollusk shells and a ^{14}C conventional age of 4500 ± 130 yr BP (GSC-6087) obtained from limnic peat collected from the same layer directly above the alluvial sediments, a correction factor of about 380 years could be applied. This gives an approximate date of 4830 years BP for the shells collected in the top part of Unit C. Limnic peat in unit B1 was dated at 4650 ± 90 yr BP (GSC-6077), and the overlying basal fen peat in unit A at 4140 yr BP (GSC-6052), indicating that between approximately 4.7 and 4.1 ka (600 years), a thin limnic peat layer of highly decomposed organic material accumulated slowly in a marsh-bordered pond before fen peat started to accumulate at 4.1 ka BP

The stratigraphic sequence presented here suggests major changes in depositional environments, from alluvial to shallow lacustrine at about 4.7 ka (maximum at 4.83 ka to minimum at 4.5 ka), which can be interpreted as the abandonment of the Minago River channel, and from lacustrine to a sedge bog at 4.1 ka. The date of 5860 ± 60 yr BP (TO-4910) on mollusk shells enclosed in alluvial sediments from a site located 800 m south of the Minago River core, within the southern arm of the channel (McMartin, 1996), is probably not significant in terms of maximum age of channel abandonment. This site is 5 m higher than the bottom of the channel in both arms, and was therefore abandoned earlier than the rest of the channel. The younger date of 2530 ± 70 yr BP (GSC-5880) obtained on basal fen peat collected at the highest rock bottom altitude of the channel (259 m), and located directly on the present-day drainage divide between waters flowing into Saskatchewan River and those flowing in Minago River (McMartin, 1996), still provides a minimum age for channel abandonment. However, this site was probably not the most favorable for peat accumulation judging by the thickness of the peat layer (75 cm), and since it has a rock bottom and is located at the edge of the fen. Moreover, this site would have been the first area abandoned by the river, hence should have a slightly older age than other parts of the channel now draining towards the Nelson river. Therefore, the mid-Holocene timing (4.7 ka) for channel abandonment confirmed by the new dates and by pollen stratigraphy remains the most reliable maximum age for the interruption of the Saskatchewan River drainage and the beginning of peat accumulation in the channel.

Dates of basal fen peat across west-central Canada indicate that fen peat deposition began <6000 yr BP in a broad zone north of the present-day grassland and south of approximately 54°30' (Zoltai and Vitt, 1990), which would include the Minago River channel area. A delay of about 3000 years in the establishment of fen peat forming vegetation overlying mineral soil is observed at several sites located in the peatlands surrounding the Minago River channel: 4900 ± 100 yr BP (BGS-868), 4930 ±100 yr BP (GSC-5931), 4500 ± 120 yr BP (GSC-1958) and 4640 ± 100 yr BP (BGS-856). However, the delay is only about 1500 years for basal fen peat overlying limnic peat: 6500 ± 150 yr BP (BGS-866) and 5975 ± 210 yr BP (S-2571). Moreover, Zoltai and Vitt (1990) found that dates on basal limnic peat samples from this area show little or no delay in limnic peat forming vegetation: 8080 ± 150 yr BP (GSC-1825) and 7255 ± 250 yr BP (S-2572). This confirms that the mid-Holocene radiocarbon age on limnic peat from the Minago River core is a reliable maximum age for channel abandonment.

ACKNOWLEDGMENTS

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TABLE 1
Radiocarbon dates in the Minago River channel area

Location	Radiocarbon age (years B.P.)	Lab No.	Reference	Comments
54°13'N, 99°10'W	4140 ± 90	GSC-6052	This paper	Basal fen peat (222 cm depth)
54°13'N, 99°10'W	4650 ± 90	GSC-6077	This paper	Limnic peat (235 cm depth)
54°13'N, 99°10'W	4500 ± 130	GSC-6087	This paper	Limnic peat (238 cm depth)
54°13'N, 99°10'W	4880 ± 60	TO-5699	This paper	Freshwater shells in limnic peat (238 cm depth)
54°13'N, 99°10'W	5210 ± 60	TO-5700	This paper	Freshwater shells in alluvial sediments (245 cm depth)
54°04'N, 99°35'W	2530 ± 70	GSC-5880	McMartin, 1996	Basal fen peat on rock bottom
54°12'N, 99°10'W	5860 ± 60	TO-4910	McMartin, 1996	Freshwater shells in alluvial sediments

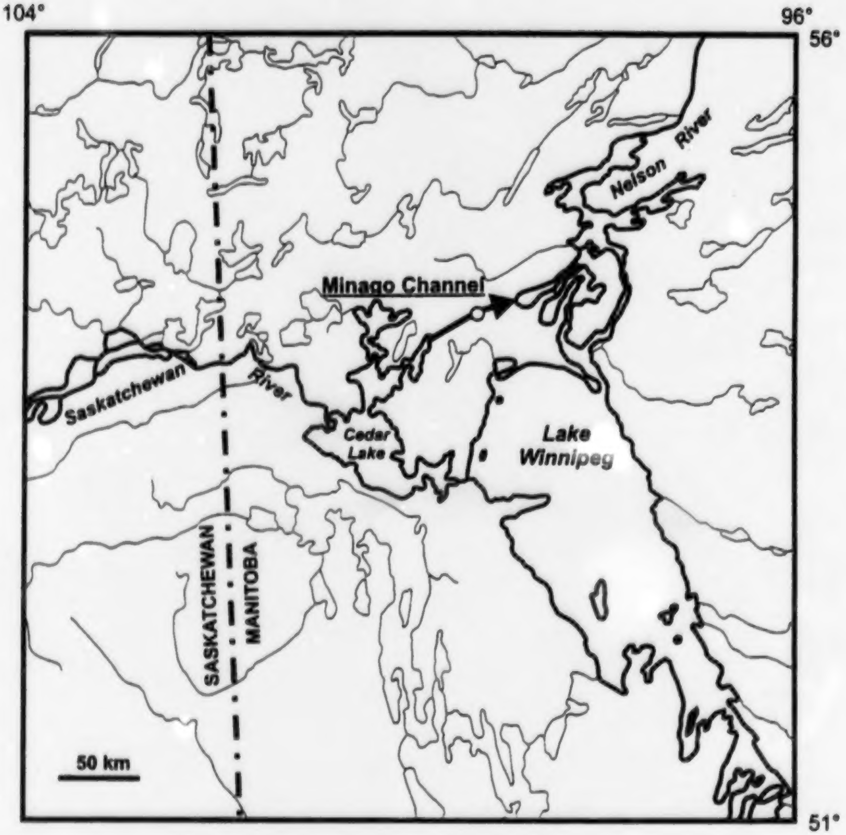
104°
96°
56°
51°
Nelson River
Minago Channel
Saskatchewan River
Cedar Lake
Lake Winnipeg
SASKATCHEWAN
MANITOBA
50 km

Figure 1. Location map of the Minago River channel area. The Minago River core site is identified as a circle.

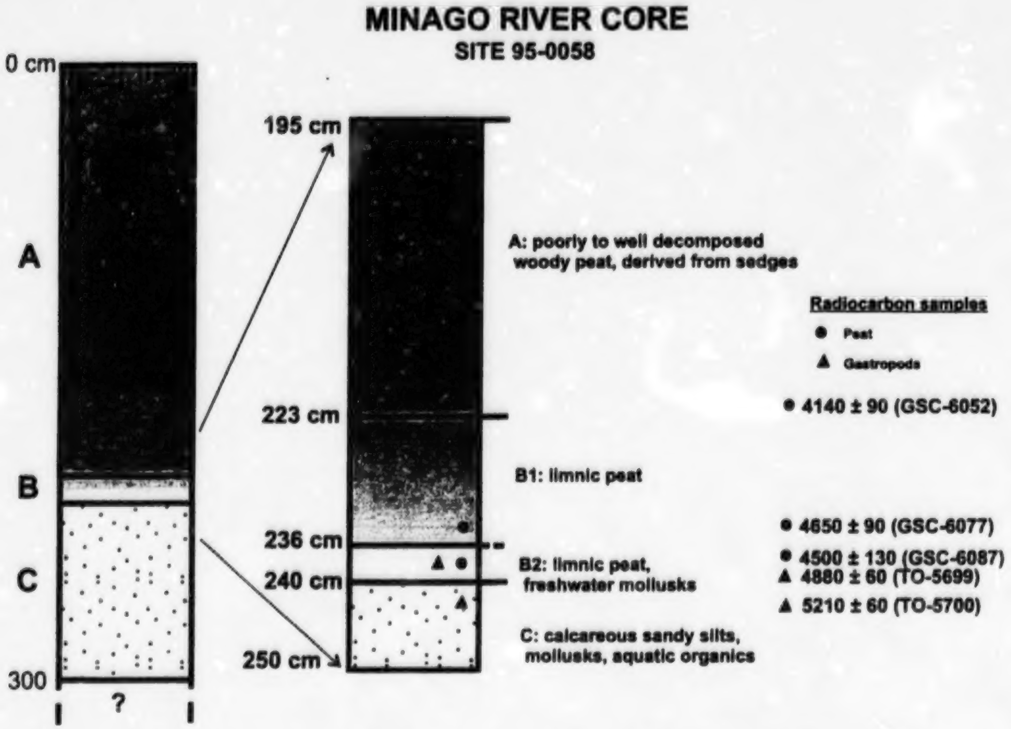
MINAGO RIVER CORE
SITE 95-0058
0 cm
A
B
C
300
?
195 cm
223 cm
236 cm
240 cm
250 cm
A: poorly to well decomposed woody peat, derived from sedges
Radiocarbon samples
● Peat
▲ Gastropods
● 4140 ± 90 (GSC-6052)
B1: limnic peat
● 4650 ± 90 (GSC-6077)
● 4500 ± 130 (GSC-6087)
▲ 4880 ± 60 (TO-5699)
B2: limnic peat, freshwater mollusks
▲ 5210 ± 60 (TO-5700)
C: calcareous sandy silts, mollusks, aquatic organics

Figure 2. Stratigraphy and radiocarbon dates in the Minago River core.

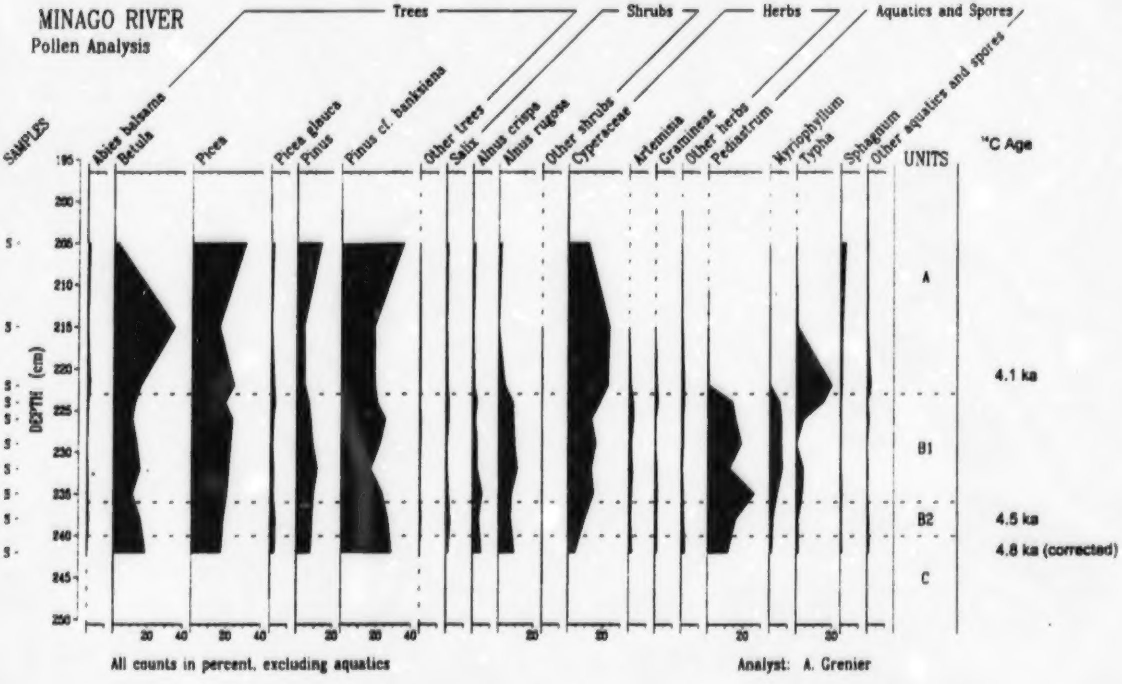

Figure 3. Pollen stratigraphy in the Minago River core (205 to 242 cm depth).

9.5 LAKE WINNIPEG SHORELINE EVOLUTION: BARRIER GROWTH AND SHORE PROFILE RECESSION

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INTRODUCTION

Background and objectives

Lake Winnipeg is the seventh largest lake in North America and a feature of great prominence in the landscape of Manitoba (Fig. 1). Prior to the initiation of the Lake Winnipeg Project in 1994 (Todd et al., 1996, 1998; Thorleifson et al., 1998), little information was available on the geology beneath Lake Winnipeg and knowledge of deposits formed in the lake was restricted to limited bottom sampling programs (Kushnir, 1971; Brunskill and Graham, 1979). Understanding of shoreline geomorphology and processes was somewhat better (e.g. Penner and Swedlo, 1974; Galay, 1974; Nielsen and Conley, 1994), but was largely confined to the South Basin (Fig. 2).

Shoreline recession and associated property losses have long been recognised as a problem in the more heavily populated South Basin region of Lake Winnipeg (Manitoba Water Resources Division, 1977). Although there is abundant evidence from historical maps and air photographs to show that rapid erosion of South Basin shores was occurring prior to dam construction on the Nelson River outlet in the 1970s (Penner and Swedlo, 1974; Nielsen and Conley, 1994), increasing public concern pointed to the need for a more detailed understanding of lakeshore gemorphology and processes (Penner and Doering, 1995; Doering, 1995).

As part of the Lake Winnipeg Project, therefore, shoreline mapping was undertaken for the first time around the entire perimeter of Lake Winnipeg (Forbes and Frobel, 1996). Apart from a descriptive classification of shore types, intended as a basis for evaluating shoreline stability, a primary objective of this work is to decipher the history of shoreline evolution in relation to crustal tilting and associated southward lake expansion (Thorleifson, 1984, 1995; Lewis and Todd, 1996a; Lambert et al., 1998), climate-induced lake-level changes (Lewis et al., 1998a, 1998b), and other factors affecting lake level, storminess, and wave climate over the past 100 to 2000 years. In the long run, this approach serves not only to support the paleolimnological investigations in the lake, but should also provide a stronger basis for understanding and predicting rates of shoreline erosion.

The initial mapping work in 1994 (Forbes and Frobel, 1996) documented the existence of coastal sediment bodies holding great potential for paleolimnological interpretation in many parts of the lake (Forbes, 1996). These include prograded beach-ridge sequences, sandy spits, gravel barriers, coastal dunes, and marsh complexes. Many of these, though recording phases of local sediment surplus and coastal accretion, are also marked by shoreline truncation or other evidence of lakeshore transgression (Fig. 3). Erosional features of this kind are found not only at the southern extremity of the lake, where isostatic tilting is known to be a factor in the shoreline recession (Nielsen and Conley, 1994; Nielsen, 1996; Lewis and Todd, 1996a; Tackman et al., 1998), but also near the northern outlet, where tilt-induced transgression is minimised. The geological character of the shoreline in many parts of the lake is also compatible with long-term recession on a time scale of the order of decades to centuries.

These observations raise important questions about the nature of shoreline development and the causes of shore erosion in various parts of the lake. In this context, the present report has two major objectives:

1 - to examine the geomorphology of large spits and barriers in various parts of the lake for evidence of their source, stability, and growth pattern over the past few hundred to few thousand years; and
2 - to consider the evidence for a variety of shoreline retreat mechanisms, including barrier breaching, washover, cliff erosion, and subaqueous downcutting and the implications for long-term lake-level changes and shoreline stability.

Geographic setting and physical limnology

With a surface area of 24 400 km², Lake Winnipeg is among the dozen most extensive freshwater lakes in the world (Nielsen and Conley, 1994). It is divided into shallow north and south basins with maximum depths <19 m and <13 m, respectively, connected by narrow passages >60 m deep in places (Fig. 1). The name of the lake is derived from *win-nipi*, the Cree expression for murky water (McGinn, 1988), a description that aptly describes the high turbidity in the lake. Sources of suspended sediment include erosion of muddy cliffs in the South Basin as well as at the north end of the lake (Franklin, 1823; Tyrrell, 1890), erosion of glacial-lake clay exposed on the shoreface throughout the lake (Penner and Swedlo, 1974; this paper), wave-driven resuspension of bottom muds, and the pea-soup appearance of thick algal blooms that commonly develop in late summer (Brunskill et al., 1979). The principal fluvial source of suspended sediment is the Red River, entering at the south end of the lake (Kushnir, 1971). Sediment input from other rivers is limited, in part because of natural lake storage and artificial impoundment in the Winnipeg and Saskatchewan River basins (Mackenzie, 1801; Brunskill and Graham, 1979).

Wind-generated waves are a major cause of shore erosion and sediment transport in Lake Winnipeg, but available data are limited. Non-directional wave data were recorded off Gimli and Grand Marais (South Basin) in 1971 and 1972 (Penner and Swedlo, 1974) and again in the central South Basin in 1996 (Doering and Fuchs, this volume). Based on the early 1970s data, the 1% exceedence significant wave height was 1.8 m and the equivalent peak period was 6 s in the South Basin (Penner and Swedlo, 1974). Significant wave heights of 4 m were reported in the North Basin in 1996 (weather radio reports from North Basin meteorological buoy) and the most energetic record obtained in the South Basin during this project (17 October 1996) had significant wave height of 1.83 m and peak period of 4.56 s (Doering and Fuchs, this volume). Wind setup of at least 1.15 m has been observed at Gimli and differences of similar magnitude are recorded between the north and south ends of the North Basin (Penner and Swedlo, 1974). Wind-driven transfers between the North and South Basins drive high velocities through The Narrows (Kenney, 1979). Large-scale bedforms observed in The Narrows (Todd and Lewis, 1996) and shore-zone morphological features analogous to tidal inlets, flood-tidal deltas, and low-tide terraces, among others, are clear responses to wind-driven water-level fluctuations throughout the lake (Einarsson and Lowe, 1968; Hamblin, 1976).

Among the outstanding issues to be resolved for an understanding of shoreline evolution in any setting are the nature, causes, and effects of variation in water levels (e.g. Bruun, 1962; Curray, 1964; Cowell and Thom, 1995). Lake levels are recorded at a number of stations around the perimeter of Lake Winnipeg (Tackman and Currey, 1996; Tackman et al., 1999). Data from Berens River, in the southern North Basin, provide a continuous record from 1914 to the present (Fig. 4). Lake levels were predominantly low from 1914 to 1926 (mean 217.35 m), although higher levels occurred in 1916-1917. Following a short-lived peak in 1927, they were even lower through much of the 1930s, dropping to their lowest recorded level in December 1940, before rising again. Water levels were much higher through the 1950s before dropping in the early 1960s. During the 12 years prior to 1976, when a control structure was built on the Nelson River near the outlet of Lake Winnipeg, lake levels were exceptionally high, averaging 217.96 m (Nielsen and Conley, 1994). Since construction of the dam, the levels have remained within historical limits. In a pre-regulation study in the early 1970s, Penner and Swedlo (1974) reported minimum and maximum observed daily extremes of 216.0 and 219.1 m, respectively, and a 50-year mean water level of 217.4 m (1918-1967).

The decadal-scale patterns of high and low lake level described above are consistent with evidence for persistence (serial correlation) in hydrological records. This is known to occur in river flows and has been demonstrated for the flood record in the Red River valley (Booy and Morgan, 1985), where clustering reduces estimates of return period for the 1826 and 1950 floods from 1250 and 29 years to 250 and 16 years, respectively. The back-to-back occurrence of high flood discharge in the Red River in 1996 and 1997 may be another manifestation of this effect, contributing in part to above-average water levels in Lake Winnipeg. The implication for shore-zone paleolimnology is that higher-than-average lake levels may occur naturally in clusters, causing temporary conditions of high runup, washover, accelerated shoreline recession and profile adjustment, as observed in the Great Lakes in the 1970s and 1980s (Moulton and Cuthbert, 1987).

Freeze-up typically occurs in mid-November, with lake ice at Gimli achieving a maximum thickness of about 1.0 ±0.2 m in mid-April, immediately before breakup (Canada AES, 1992). Pressure ridges develop at consistent locations within the lake and pressure-ridge keels interact with the lakebed to form extensive scours (Todd et al., 1997). Ice-push at the lakeshore has been observed to cause minor scour, damage to vegetation, and structural damage at various locations (Penner and Swedlo, 1974; Nielsen and Conley, 1994; Forbes and Frobel, 1996).

Lakeshore geology and geomorphology

The regional geology on the east side of the lake is dominated by resistant Archean shield rocks of the Superior Province (Manitoba Mineral Resources Division, 1979; Teller and Bluemle, 1983; Todd et al., 1998), with limited surficial sediment cover. Ordovician clastic and carbonate rocks crop out along the western and southeastern shores (Bezys, 1996; Todd et al., 1998), with a variable cover of glacial, glaciofluvial, and glaciolacustrine sediments. Thin, loose, sandy till forms a discontinuous veneer on shield rocks east of the lake (Tyrrell and Dowling, 1900), where the overburden thickness is generally <10 m. Multiple tills are present over Paleozoic rocks west of the lake (Klassen, 1967; Nielsen, 1989), where the overburden thickness is typically <20 m but locally up to 50 m along the west side of the South Basin (Nielsen and Thorleifson, 1996). Thick multiple tills and subaqueous outwash deposits are present in the north-south trending Belair Moraine along the southeast shore of the South Basin (Lebedin, 1978; Matile and Groom, 1987). An extensive body of fine-grained sediment associated with the Hargrave Moraine complex (Tarnocai, 1970; Klassen, 1983) has been mapped along the north and northeast shores of the North Basin, where it forms prominent bluffs (Nielsen and Thorleifson, 1996). The prominent Long Point peninsula in the North Basin is associated with a major Quaternary glacial moraine complex, The Pas Moraine (Klassen, 1967; Todd et al., 1998). Coarse outwash deposits forming bluffs, boulder beaches (Dowling, 1900) and nearshore boulder lag deposits (Forbes et al., this volume, b) on George Island in the central North Basin are associated with the George Island Moraine (Nielsen and Thorleifson, 1996; Todd et al., 1998). Silty clays of glacial Lake Agassiz (Upham, 1895) form a broad plain bordering the southwest end of the lake (Teller et al., 1983). Boulder-rich tills or outwash deposits are exposed in various places around the South Basin. The Red River enters the lake through a wide deltaic marsh complex, Netley Marsh (Fig. 2), which is slowly being inundated as isostatic tilting causes the water level at the south end of the lake to rise (Johnston, 1946; Nielsen and Conley, 1994; Lewis and Todd, 1996a; Lambert et al., 1998).

Shore type is a complex function of geological inheritance, sediment supply, lake-level history, fetch length and exposure, wave climate and other shore-zone processes acting at a given location along the present lake shore. In settled areas it can also be modified by artificial structures or other human activities. In Lake Winnipeg, as in other large lakes, the underlying geology exerts a strong influence on the distribution of shore types and rates of shoreline erosion (Gelinas and Quigley, 1973). Five principal subdivisions based on shore-zone geology can be distinguished in Lake Winnipeg, as follows:

- shores on Precambrian shield (east side of the lake),
- shores on Ordovician carbonate and sandstone lithologies (primarily west side of lake),
- shores in Late Quaternary glacial tills, outwash, and related deposits (various locations),
- shores in Late Quaternary glaciolacustrine silty clays (various locations),
- wetland deposits (most prominent at south ends of major embayments).

Parts of the eastern shore of the lake (Fig. 1) are characterised by Precambrian exposures virtually devoid of modern sediments (the Kasakeemeemisekak Islands archipelago is one such area), whereas other parts of the east coast have access to sediment sources enabling the development of extensive sandy barriers with large coastal dune complexes (e.g. the Spider Islands barrier north of Bélanger River), as described in this report.

In many areas, Quaternary glacial, proglacial, and postglacial deposits effectively mask the underlying bedrock (Manitoba Mineral Resources Division, 1981; Todd et al., 1998) and control the topography and sediment supply. Ice-contact and proglacial deposits with significant proportions of cobbles and boulders (tills, outwash gravels and sands, and glacio-lacustrine silts and sands) cover much of the eastern lakeshore of the South Basin and crop out elsewhere to form low headlands. Lacustrine silty clays of proglacial Lake Agassiz form much of the plain along the western side of the South Basin (Penner and Swedlo, 1974). Lowland areas along both sides of the lake are backed in many places by peat bogs and the shores in these areas are characterized either by low peat scarps or, where sufficient sediment is available, by thin fringing barriers.

In many cases, Lake Winnipeg beaches are confined to narrow wedges at the base of cliffs. These may be gravel beaches backed by rock cliffs, most commonly limestone and dolomite, or mixed sand-gravel beaches below cliffs cut into unlithified but often well consolidated deposits of glacial till, outwash silts and sands, or glaciolacustrine silty clays. Elsewhere they form thin beach veneers (Penner and Swedlo, 1974; Nielsen and Conley, 1994) or thicker transgressive barrier systems, often with large dunes, moving slowly onshore and reworking older shore deposits. Large coastal dunes are present in other settings, as at the west end of George Island, where they are up to 15 m high. Multiple nearshore bars occur in some places but single bars in nearshore sands of limited lakeward extent are more common.

Various classifications of shore type and vulnerability can be found in the literature (e.g. Fricker and Forbes, 1988; Stewart and Pope, 1993; Howes et al., 1994; Sherin and Edwardson, 1996; Shaw et al., 1998) and each has utility for a particular application. Penner and Swedlo (1974) developed a lakeshore classification for the South Basin of Lake Winnipeg, involving 12 shore types distinguished on the basis of substrate, bluff or backshore height, beach volume and morphology. Forbes and Frobel (1996) proposed a 15-type shoreline classification for the entire lake, grouped into seven shore-type associations, which can be summarized as

A - marshy shores;
B - Precambrian outcrop shores with very limited beach development;
C - sandy beaches and barriers;
D - mixed sand-gravel beaches with boulder-lag or rock headlands;
E - Paleozoic outcrop shores with gravel beaches and barriers;
F - cliffed shores in Quaternary deposits;
G - artificially modified or protected shores.

This paper is concerned in the first half primarily with group C shores. In the second part of the paper, documenting shore profile recession, numerous shore types are involved, but the focus is primarily on groups C, D, and F.

Previous work

Despite a history of erosion problems, particularly in the smaller South Basin (Penner and Swedlo, 1974; Galay, 1974; Doering, 1995), there is only a small body of work on the shorelines of Lake Winnipeg and little in the past 20 years. Except for a few early geological surveys (Tyrrell, 1890; Dowling, 1900; Tyrrell and Dowling, 1900), descriptions of the shore zone have been largely restricted to the South Basin, where early work includes theses by Solohub (1967), Veldman (1969), and Cheng (1972) and a related paper (Solohub and Klovan, 1970). More recently, Nielsen and Conley (1994) published a comprehensive study of the southern lakeshore fronting Netley Marsh. The lakebed bathymetry has been charted by the Canadian Hydrographic Service (CHS, 1981, 1982, 1986).

Prior to the development of regulation structures on the Nelson River outlet in the 1970s, a comprehensive study of lakeshore processes was undertaken in the South Basin. This resulted in a large monograph (Penner and Swedlo, 1974) containing extensive data, analysis, and insight on shore-zone processes. Their work clearly demonstrated a long-term erosional tendency and proposed a link between shoreline recession and post-glacial isostatic tilting of the lake basin. A valuable popular summary, including shoreline protection recommendations, was produced by Mark Young under Frank Penner's direction (Manitoba Water Resources Division, 1977). Entitled *The Lake Winnipeg Shoreline Handbook*, this was subtitled *A property owner's guide to shoreline processes and erosion protection structures on the Southern Pool of Lake Winnipeg*. One figure in this handbook demonstrated the correlation between shoreline erosion rates at a site north of Gimli (site 8031 described later in this report) and mean monthly lake levels during four open-water seasons (1972 to 1975). It showed the annual erosion rate increasing by a factor of 22 between 1973 (0.3 m) and 1974 (6.7 m), while maximum monthly water levels increased from 217.7 m in July 1973 to 218.9 m in July 1974 (Fig. 4).

Using historical data (land subdivision surveys from 1874 to 1934), new shore surveys (1971-1973), and air photos (1946 to 1971), Penner and Swedlo (1974) computed rates of shoreline recession in the southern South Basin ranging from 0.0 to 7.6 m/a. They also reported mean rates by shoreline reach (Fig. 2). Accretion was observed almost exclusively at artificial barriers where sediment moving alongshore was trapped against breakwaters or groynes. The most rapid erosion rates (>2.5 m/a) were mapped at a site south of Riverton, along a stretch of shore north of Gimli, between Gimli and Willow Point, near Sans Souci at the west side of Netley Marsh, along most of the marsh shore east of Pruden Bay, and on part of the Patricia Beach and Beaconia barrier at the southeast corner of the lake (Figs 11-1 to 11-5 of Penner and Swedlo, 1974). Rates of erosion along the eastern shore between Beaconia and Elk Island were generally less, largely because of the more resistant shoreline materials there (rock, ice-contact deposits, and outwash gravels) relative to the silt- and clay-dominated western shore. Nevertheless, rates as high as 2 m/a were recorded south of Grand Marais and recession rates >0.5 m/a were found in a number of places.

The stratigraphy of lake bottom sediments in Lake Winnipeg has been documented in a series of seismic reflection profiles and sediment cores obtained in the course of the Lake Winnipeg Project (Todd and Lewis, 1996; Lewis and Todd, 1996a, 1996b; Todd et al., 1998; Lewis et al., this volume, a, Forbes et al., this volume, b). In general terms, acoustic basement (Precambrian shield rocks on the east side and Paleozoic sedimentary rocks on the west) is overlain by a succession of discontinuous ice-contact deposits and conformably draped glaciolacustrine silty clays (termed the ***Agassiz Sequence***, Todd et al., 1998). This sequence, deposited in proglacial Lake Agassiz between about 11 and 8 ka, is cut by a widespread planar unconformity (informally the *Agassiz Unconformity* or AU), overlain by onlapping, nearly flat-lying clay muds (termed the ***Winnipeg Sequence***, Todd et al., 1998) and small localized deposits of littoral sands and minor gravel.

A growing body of published geological evidence points to significant variations in lake level at longer time scales (hundreds to thousands of years), forcing extensive migration of the shoreline, particularly in the southern parts of the North and South Basins (Lewis and Todd, 1996a; Nielsen, 1996, this volume; Todd et al., 1997; Lewis et al., 1998a, 1998b). The predominance of shoreline retreat toward the south or southwest reflects the importance of southwestward isostatic tilting, revealed in part by studies of tilted beaches of glacial Lake Agassiz and successor lakes (Johnston, 1946; Thorleifson, 1983; Nielsen et al., 1987; Tackman and Currey, 1996). The tilting results from differential uplift of the lake outlet, at the north end of North Basin, relative to other parts of the lake where uplift is less rapid (Penner and Swedlo, 1974; Thorleifson, 1984, 1995; Lewis and Todd, 1996a, Tackman et al., 1998). In addition to the tilting process, which can explain southward transgression of the lake, basin-wide fluctuations in lake level are believed to have occurred in response to climatic variations in the water balance (Nielsen, 1996; Lewis et al., 1998a, 1998b) or to major changes in drainage, such as diversion of the Saskatchewan River into Lake Winnipeg approximately 4.7 ka (McMartin, 1996, this volume) and switching of Assiniboine River drainage between Lake Manitoba and Lake Winnipeg via Red River (Rannie et al., 1989). The combined effect of all the above changes, including a transfer of outlet control from Warren Landing north to Whisky Jack Narrows on the Nelson River (Lewis and Todd, 1996a), has been to raise water levels either gradually or by discrete increments over several thousand years (Lewis et al., this volume, a). These changes are recorded in the coastal geomorphology and shore-zone sedimentation patterns of Lake Winnipeg, not only in the South Basin but throughout the lake, as demonstrated in this report.

Methods

This paper is based primarily on the results of two field programs. The first was an aerial and ground reconnaissance in September 1994 (Forbes and Frobel, 1996), using road transport and a Cessna-185 aircraft (CF-YYZ) on floats. This followed a month-long scientific cruise on the lake in August of that year (Todd et al., 1996). The second was a more extensive nearshore and shoreline survey carried out using an open boat (7 m Lake Winnipeg yawl) deployed from CCGS *Namao* in August-September 1996 (Todd and Forbes, this volume). Supplementary data were provided by a survey and coring program in March 1997 (Forbes, in prep.), using road transport and Bombardier™ snow vehicles chartered from local fishermen for work on the ice, as well as aerial reconnaissance using a ski-equipped Cessna-185 aircraft (CG-CKZ), repeated in late April 1997.

The morphosedimentary data on shore-zone deposits presented in this paper are derived from vertical and oblique air photo interpretation, from shore surveys and sampling at approximately 25 locations throughout the lake, and from published data on shoreline geomorphology in the South Basin (notably Penner and Swedlo, 1974; Nielsen and Conley, 1994). Nearshore surveys of the lakebed were completed at 20 locations in 1996 (Fig. 1). Details of the equipment and methods are given in Forbes et al. (this volume, a).

In addition to the nearshore grab sampling program (Appendix 10.7, this volume), samples were collected onshore in 1994, 1996, and 1997. A limited coring effort was undertaken in 1994, using a Hiller peat borer. This device has a solid auger bit and a 0.5 m long hollow chamber, ~0.03 m inside diameter, with a rotating cutter lid. In March 1997, additional cores were obtained from the ice with 3-inch (~0.08 m) diameter aluminum tubes driven into the lakebed (Forbes, this volume, a). Samples of organic material were sorted for identifiable plant macrofossils and AMS radiocarbon ages (Vance and Telka, 1998; Telka, this volume, and Appendix 10.6, this volume). Rooted tree stumps below present lake level were sampled at a number of locations (Nielsen, this volume) and their ages determined by conventional radiocarbon dating. Radiocarbon ages were converted to calendar ages using CALIB v. 3.03 and a range of 1σ (Stuiver and Reimer, 1993).

DEPOSITIONAL SHORE-ZONE FEATURES IN LAKE WINNIPEG

This section examines a number of spit, barrier, and beach-ridge complexes in various parts of the lake. These depositional systems are the major sinks for sand and gravel supplied to the coastal system through shoreline and shoreface erosion and (in a few localities) by rivers. Where positive sediment budgets have favoured beach-ridge progradation or spit extension (Figs 3 and 5), these coastal deposits may hold a significant paleoenvironmental record (Forbes, 1996). This has been well demonstrated by studies of beach-ridge systems on other large lakes (e.g. Thompson, 1989, 1992; Chrzastowski et al., 1994; Thompson and Baedke, 1995), as well as by a limited body of earlier work on abandoned beach deposits of glacial Lake Agassiz and successor lakes (e.g. Nielsen et al., 1984, 1987; McMartin, 1996).

Spits and prograded beach-ridge systems in Lake Winnipeg

At a number of sites along the eastern and western shores of the North Basin, progradational beach-ridge complexes are found in association with rock or till-lag headlands. Examples include Morass Point and other nearby systems on the western shore of North Basin south of Gull Bay (Figs 1 and 5) and extensive sandy beaches with dunes in the Whoopee Harbour, Flour Point, and Catfish Point area south of Berens River on the eastern shore (Forbes and Frobel, 1996). At McKay Point (Fig. 6), north of Berens River, older beach and dune ridges are present landward of the active beach, particularly but not exclusively on the northern (updrift) side of the headland.

These areas of sediment progradation are most readily explained as products of longshore transport, with deposition and beach-ridge growth occurring on the updrift sides of headlands, which act as transport barriers. Alternatively, changes in shoreline orientation at subtle headlands such as McKay Point may cause longshore changes in the sediment transport capacity, thereby favouring progradation. In such cases, positive feedback could lead to foreland growth if sufficient sediment were available. However, supplies of fresh sediment along these shores are limited and much of the sand may be retained or recycled from earlier shoreline deposits.

Areas of abundant gravel supply with limited volumes of sand are characterized by small gravel barriers and simple flying spits, occasionally with minor recurve development. These are found at a number of sites, such as Sturgeon Gull Harbour and Fiddler Point along the western shore of the North Basin north of Grand Rapids and at numerous other small headlands such as Bushy Point south of The Narrows (Fig. 7a of Forbes and Frobel, 1996). A small gravel foreland at the southeast end of Black Bear Island, north of The Narrows, was surveyed as part of this project in 1996 (see illustration in Dowling, 1900).

In a few locations, well-developed recurved spits have developed in sands with small admixtures of gravel. These include Limestone Point (see following section) and the barrier across the mouth of Bélanger River. A small spit foreland with multiple recurve structures has developed at Jackfish Point on the south side of Traverse Bay (Fig. 2). A large truncated system of beach ridges on the south-side barrier at Gull Bay, in the North Basin, has the appearance of recurved ridges originally constructed by spit extension from the north (Fig. 3). This is compelling evidence for the former existence of a large spit extending all the way across the bay. At some time, this spit was breached at a narrow neck in the middle, producing the two opposing spits (North Bar and South Bar) observed at the north and south sides of the bay today.

Large constructional barriers

Limestone Point spit

The 20 km spit forming Limestone Point (Figs 7 and 8), in the northwest corner of the North Basin, is the largest coastal feature on Lake Winnipeg. Recurved beach ridges attest to the construction of this spit by longshore drift from the east. The north shore of the North Basin is dominated by eroding bluffs up to 12 m high (Forbes and Frobel, 1996), composed of fine-grained sediments including "stiff blue clay" overlain by peat (Tyrrell, 1890; Nielsen and Thorleifson, 1996). This material, forming part of the Hargrave Moraine (Tarnocai, 1970), extends in a broad arc across the north end of the lake, including exposures near Montreal Point southeast of the Nelson River outlet. With a gradual reduction in backshore elevation toward the west, the cliffs give way to a fringing sandy beach and foredune ridge a short distance east of the head of Limestone Bay, but the planform arc of the coast continues unbroken along the spit to Limestone Point.

The spit comprises three distinct bundles of recurved beach and dune ridges (I, II, and III in Fig. 8) with intervening narrow sections. These suggest three distinct pulses of westward growth toward the present distal terminus (Fig. 7), just 3 km from the western shore of the lake. The overall morphology of Limestone Point displays a typical spit structure with a narrow feeder section leading to the wide, recurved, downdrift sediment sink (ridge bundle III in Fig. 8). Bundles I and II represent earlier terminal positions of the spit and the overall morphology implies three distinct intervals of slow spit growth separated by episodes of rapid extension. At the distal end of the spit, it has now entered a fourth phase, controlled by wave refraction around McIntosh Reef. In the lee of this rock shoal, the beach is prograding lakeward to form a wide, dissipative, tombolo-like platform with a ridge-and-runnel bar complex backed by marsh (Fig. 7). Much of the sediment arriving alongshore from the east is now contributing to this progradation rather than to spit extension.

Behind Limestone Point, an extensive progradational beach-ridge complex has accumulated at the east end of Limestone Bay (Fig. 9). This comprises a sequence of individual beach ridges with a total width (normal to the shore of Limestone Bay, parallel to the modern Lake Winnipeg shoreline) of about 500 m. The inner bayhead beach today consists of sandy fine gravel, with well-rounded coarse pebbles in the lower foreshore. A wooded dune ridge separates the inner shore from the exposed Lake Winnipeg beach at the proximal end of the spit. This feature extends eastward in front of the truncated beach-ridge complex as a transgressive dune ridge (Fig. 12 of Forbes and Frobel, 1996). Exploration along both the outer beach and the inner margin of the dune ridge revealed no exposed beach-ridge sediments. Numerous auger probes encountered silty sand beneath a thin peat cover. A short core was obtained at the inner end of the survey profile (Fig. 14 of Forbes and Frobel, 1996). The lithostratigraphy of this core consisted of poorly sorted silty medium sand overlain by 0.43 m of compact peaty mud beneath 0.38 m of muddy peat. The sand is interpreted as a beach-ridge deposit or possibly an early trough infill, underlying wetland peat that has accumulated over the low-lying central portion of the beach-ridge complex (Fig. 9). A collection of 21 *Potentilla norvegica* (cinquefoil) seeds (picked and identified by Alice Telka, Appendix 10.6, this volume) from near the base of the peaty mud unit returned an AMS age of 930±90 radiocarbon years BP (CAMS-34553). The equivalent calendar age is estimated between 934 and 728 years BP (1016 to 1222 AD). This is a minimum age for the central part of the beach-ridge complex. It also dates the proximal part of Limestone Point spit, which was required to provide a protected setting in which the beach ridges could accumulate.

Assuming that this provides a reasonable date for completion of the first phase of extension on the Limestone Point spit, the last two phases of spit extension are younger than 900 years. Furthermore, the elevation of sand at the base of the core and the wetland growth over the central and inner part of the beach-ridge complex are consistent with a limited rise in lake level at this site over the past 700 to 1000 years. A submerged ridge with aquatic growth, parallel to Limestone Point spit in Limestone Bay (Forbes and Frobel, 1996), is an enigmatic feature, possibly an earlier fringing barrier or dune ridge associated with lower lake levels.

Grand Beach

Several major embayments are present along the southeast shore of the South Basin (Fig. 2), hosting barrier and inlet complexes with dunes. Beaconia Beach (Patricia Bay) in the far southeast was described in some detail by Nielsen and Conley (1994). Major embayments with sandy barriers are also present at Grand Beach, Hillside Beach, and on the south side of Elk Island. Much of this coast has cliffs cut into glacial till and other ice-contact or proglacial heterogeneous deposits of the Belair Moraine (Lebedin, 1978; Matile and Groom, 1987), forming resistant headlands that define the major north- to west-facing embayments. These glacigenic deposits contain a large proportion of cobbles and boulders, including some very large blocks, which armour the shore in places (Penner and Swedlo, 1974), as on the south side of Grand Marais Point (Doering, 1995; Forbes and Frobel, 1996).

Grand Beach has developed by accumulation of southward-moving sediment against the natural groyne of Grand Marais Point. There is little sediment movement around this point and most material produced by shore erosion south of Ironwood Point moves either offshore to deep water or alongshore to accumulate at Grand Beach. This barrier has a large central inlet and flood delta (Fig. 10) and a low-angle dissipative nearshore profile with a 'low-tide' terrace, subtle ebb shoal, and low-relief bars (Forbes and Frobel, 1996). The shoreface becomes steeper lakeward across a convex profile extending approximately 200 m out to a roughly horizontal bottom in about 3 m water depth. Although Penner and Swedlo (1974) recorded local progradation in the central part of Grand Beach, with minor erosion at the southwest and northeast ends, the very low-angle foreshore slope makes any photogrammetric interpretation suspect. There is clear field evidence for backshore erosion at the northeast end of the beach. The Grand Beach barrier is dominated by coastal dunes up to 10 m high. These have large blowouts feeding parabolic lobes advancing landward over the backbarrier flats (including the parking lot in the background of Fig. 10) and into the lagoon. The dunes are typically about 65 m wide in this area and are suffering from excessive recreational pressures (Doering, 1995). Despite a long-term slow transgressive tendency implied by the barrier morphology, inset against Grand Marais Point, with a backbarrier lagoon and flood delta, the Grand Beach barrier complex may be building primarily upward with rising lake levels.

Disbrowe Point spit

This prominent feature (Fig. 11) extends about 5 km south-southwest across the front of Paterson Bay (Fig. 6), extending the line of the coast from the north in a continuous shallow arc. The complex history of this feature makes it difficult to classify. Although it may properly belong with the transgressive barriers later in the paper, it is introduced here because of its present morphology as a prominent flying spit.

The barrier has a narrow neck, about 75 m wide, at its mid-point and a bulbous beach-ridge complex, more than 600 m wide, at its distal end (Fig. 12). Narrow proximal or central necks and wide terminal ridge complexes are typical features of spits, reflecting both entrainment of proximal spit material into the longshore transport corridor (Kidson, 1963) and, in some cases, landward migration of the proximal or central section (Davidson-Arnott and Fisher, 1992; Ollerhead and Davidson-Arnott, 1995), sometimes leading to breaching (Shaw and Forbes, 1992). In this sense, Disbrowe Point is not atypical. However, the distal end of this spit-like barrier has a very unusual pattern of beach ridges. In contrast to the typical recurved morphology (Zenkovich, 1967), as represented at a number of locations described earlier, Disbrowe Point has several intersecting beach ridges all broadly parallel to the present shoreline. Only a small volume of sediment at the very distal tip of the point shows the typical recurved morphology of most true spits (Fig. 12).

Comparison between the 1934 shoreline, mapped as part of a hydrographic survey (CHS, 1935) with the ridge morphology mapped from air photos and a shoreline survey completed in September 1996 (Fig. 12) shows a number of salient points. The outer face of the spit has been cut back and sediment has been carried around the tip to the landward side of the terminal lobe, increasing its width without significant longshore extension, possibly because of strong currents in the navigation channel, direct wave attack on the distal beachface, or a combination of the two. Beach-ridge truncation is evident near the tip of the spit at control point 339 (Fig. 12). Low beach ridges have formed on the landward side, presumably by wave reworking from the south or within Paterson Bay, and these show evidence of washover in places and of local breaching at one site. In this way, distal sedimentation occurs at Disbrowe Point without generating recurved structures. On the other hand, it remains difficult to explain the formation of the east-west oriented ridges in the vicinity of control point 338 (Fig. 12) by this spit-growth mechanism.

A short distance (1 to 3 km) west of Disbrowe Point, across the Berens River navigation channel, Berens Bank forms an east-west oriented shoal with a steep, linear, north-facing lakeward margin and a gentle south-facing backslope, with depths < 1 m on the crest (Fig. 12). A line of shoals, including emergent rocks, extends toward the northwest from the minor promontory along the face of Disbrowe Point near its distal end, demonstrating that this feature reflects some wave convergence or shadow effect, similar to a failed tombolo. The beach-ridge morphology in the distal lobe of the spit indicates alternating growth from more than one direction. It is plausible to consider Berens Bank as an overstepped barrier beach and to envisage a situation in which longshore sediment transport from the west built the east-west oriented ridge components preserved at Disbrowe Point. Breaching of the former barrier by rising lake levels may have led to diversion of the Berens River outlet from a former course to the west, enabling formation or reoccupation of the present channel running north-northwest past Disbrowe Point.

Core 97301-008 was recovered through the ice in 2.6 m of water approximately 100 m lakeward of the beach just north of the neck at Disbrowe Point (Fig. 12) in March 1997 (Forbes, in prep.). It contained 0.67 m of sediment (apparent penetration 1.07 m), consisting of 0.05 m of pebbly sand over 0.29 m of peat over 0.15 m of silt and granules, unconformably overlying Agassiz Sequence glaciolacustrine clay. Two AMS ages were obtained from the top and base of the peat (Telka, this volume, and Appendix 10.6, this volume). These indicate that peat began accumulating over underlying silt, interpreted as a shallow-water deposit, at 2910 ± 50 radiocarbon years BP (*Mentha* sp. seeds, identified by A.M. Telka, CAMS-44528), 2.9 m below present lake level, and continued forming until at least 2510 ± 50 radiocarbon years BP (unidentified delicate twig with intact bark. CAMS-44527) in 2.6 m present water depth. Two conventional radiocarbon ages, obtained from *Pinus* sp. driftwood buried beneath dune sand on a surface interpreted as a former washover (Fig. 12; Nielsen, this volume), were 130 ± 70 and 260 ± 75 years BP (BGS-1910 and BGS-1911, respectively). These indicate significant wave runup sometime within 130 radiocarbon years before 1950 AD. A modern age determined for raspberry seeds (*Rubus idaeus* L., identified by A.M. Telka; CAMS-44526) from a buried soil in the dune ridge near the neck indicates that dune migration has been active in recent time.

The combined evidence at this site, including the beach-ridge morphology, the shoal bathymetry, and the lithostratigraphy of core 008, suggests that an earlier barrier may have formed across the mouth of Paterson Bay, extending from Berens Bank to the coast further north. Alternatively (or as well), the steep face on the north side of Berens Bank may represent a former shoreline scarp, which could have fed sediment eastward into the Paterson Bay embayment. Shoreline transgression into Paterson Bay may have first cut the unconformity on the underlying glaciolacustrine clay in core 008, before barrier growth formed a shallow embayment in which the gritty silt accumulated, eventually giving way to peat formation at least 2.9 m below present lake level at about 2.9 ka. The barrier at this time may have resembled the present Netley Marsh barrier at the south end of the lake, with a broad marsh area in Paterson Bay behind it. With continuing rise of lake level at the south end of the North Basin, and without a large supply of sediment from the north, this barrier would be forced into a transgressive mode, eventually overriding the site of former peat growth at core 008. Later breakup and reorganisation may account for the early east-west oriented beach ridges in the distal end of the present spit, while the shore-parallel ridges behind may have formed in a manner analogous to formation of the latest ridges since 1934 (Fig. 12).

The barrier across the north end of Berens Island (Fig. 6) is a transgressive feature with an erosional nearshore profile (Forbes et al., this volume, b) cut into deposits of glaciolacustrine silty clay (Agassiz Sequence deposits of Todd et al., 1998). Similar lakebed features in 15 m of water, in the vicinity of sample stations 210 and 211, north of Berens Island (Fig. 6), and a model of lakeshore migration under southward tilting proposed by Matile (1996), have been interpreted as indicating a pattern of transgressive shoreline migration, with landward retreat of beaches and barriers over the past 4000 years or more, culminating in the present-day barriers at Berens Island and Disbrowe Point and the remnant Berens Bank.

EROSIONAL SHORE-ZONE FEATURES IN LAKE WINNIPEG

Evidence for shoreline recession

Shoreline retreat is evident at a number of North Basin sites, including the extensive (40 km) section of bluffs across the north end of the lake between Warren Landing and Limestone Bay (Fig. 1). This feeds sediment west to the spit at Limestone Point. Shoreline retreat in this area is evident from truncation of the bayhead beach ridges by the transgressive fringing barrier along the outer shore (Fig. 9). The earliest recurves (set I) at Limestone Point spit (Fig. 8) have been largely reworked as the proximal spit has evolved and sediment has been moved downdrift to subsequent depocentres (recurve sets II and III).

The trailing shoal behind McIntosh Reef (Fig. 7) is analogous to similar structures observed behind drumlin core remnants on transgressive coasts in Nova Scotia and Ireland (e.g. Taylor et al., 1986; Orford et al., 1996), as are the trailing gravel spits and shore-normal lag shoals at Eating Point and Nistwawnayapiskaw Point (respectively north and east of Grand Rapids). At South Bar in Gull Bay (Fig. 1), south of Long Point, a complex set of old beach ridges has been truncated by landward migration of the outer shore (Fig. 3). The present spit extending north across Gull Bay is severely breached or awash along much of its length, indicating that sediment from this system is being actively reworked landward into the bay or southward alongshore into an adjoining shallow embayment.

Thin transgressive barriers moving landward across extensive bogs are present at a number of sites along the eastern shore of North Basin. Rooted stumps recovered from the lower foreshore and nearshore at Spider Islands and Marchand Point (North Basin) and Observation Point (northeastern South Basin) returned calibrated radiocarbon ages ranging from 295±75 to 1990±80 years BP (Nielsen, 1998, this volume). These attest to recent shoreline recession at these sites, as do the rooted stumps and dated peat beneath the beach at Passage Point in Fisher Bay (Forbes and Frobel, 1996). Other evidence includes the parabolic dunes and blowouts at Spider Islands, Grand Beach, and other sites, moving sand landward across the barrier into the lagoon behind. Estuarine embayments at the mouths of many rivers (Forbes and Frobel, 1996) are strongly suggestive of rising lake levels. Examples include the Bélanger, Pigeon, Winnipeg, and Icelandic Rivers (Figs 2, 6, 13).

Transgressive washover deposits analogous to those described from the Netley Marsh shore (Nielsen and Conley, 1994) are also found at the south ends of Washow, Fisher, Kinwow, and Sturgeon Bays, as would be expected from southward tilting effects.

Transgressive barriers

Spider Islands barrier

The Spider Islands barrier is a narrow transgressive tombolo system, anchored on a rock headland, one of a number of

Precambrian outcrops protruding above lake level and forming the Spider Islands proper (Fig. 13). The barrier protects a broad lagoon with a narrow connecting channel and well-developed flood-delta. The southern limb of the barrier is up to 180 m wide at the south end, but narrows toward the headland, where a broad marsh is present on the landward side. Large dunes with parabolic blowouts dominate the barrier (Fig. 13). The dunes are at least 14 m high at the southern end (Fig.14). The beach is narrow, with a low berm, a shallow subaqueous terrace, and a single nearshore bar. The outer nearshore profile is steep and concave, extending lakeward about 240 m from the bar crest to the base of sand in about 5 m water depth (Fig. 14). Beyond the base of the sand, the shoreface profile is a rough erosional surface cutting across relict Lake Agassiz muds (see section below) with occasional outcrops of Precambrian basement.

This barrier and other sandy beach systems along the eastern shore are resting on a shallow platform of Precambrian shield rocks. The absence of obvious sediment sources for these extensive coastal sand bodies led Forbes and Frobel (1996) to speculate on the existence of an offshore source on the lake floor. No such source was found during limited nearshore surveys in 1996 and the issue remains enigmatic. It is probable that the Spider Islands barrier was derived from ice-marginal deposits that are now largely exhausted, supplemented by very small quantities of sand supplied from erosion of Agassiz Sequence silty clays on the shoreface. In this scenario, the barrier developed as a paraglacial feature (cf. Forbes and Syvitski, 1994) and has reworked its finite sediment volume as the entire system migrated landward with rising lake levels.

Netley Marsh barrier

At the south end of Lake Winnipeg (Fig. 2), a thin veneer of beach sediment forms a fringing barrier along the outer lakeshore of Netley Marsh (Nielsen and Conley, 1994). Along much of its length, this barrier is migrating landward over the marsh deposits by intermittent washover, forming large sandy washover fans and splays in a number of places. The shoreline migration is also advanced by breaching of delta lakes, the most notable present example being the wide opening into Pruden Bay (Fig. 15).

The shoreface slope off the delta front is relatively gentle (0.001 to 0.006 out to the 4 m isobath; Fig. 15). East of Pruden Bay, the barrier is typically thin and low (Fig. 16 (profile 8206)), with crest elevations in the range of 218.5 to 219.2 m. It is higher (up to about 221.0 m) in an area of prograded dune ridges west of Main Channel (Fig. 16 (profile 8208), and where an eroding foredune ridge is present west of Salamonia Channel. Many sites along this shore show a very low-angle beachface or foreshore terrace, but parts of the western Netley Marsh shore are notably different. Just east of Chalet Beach, the shore is gravelly and may represent a sink for eastward longshore transport of gravel, although Penner and Swedlo (1974) concluded that the net transport direction along that section is westward toward the washover sink at Sans Souci. Veldman (1969) indicated eastward net transport at Chalet Beach, consistent with our observations.

East of Parisian Lake (Fig. 15), the beach is largely replaced by foreshore marsh. This is consistent with near-complete blockage by Stoney Point of sediment moving south along the eastern shore. The principal sediment sources for the Netley Marsh barrier are the Red River, entering west of Pruden Bay, longshore transport along the southwest shore, and landward reworking of older barrier sand. The prograded dune ridges west of Main Channel may reflect proximity to the Red River outlet, although only 3% of the river load is sand (Penner and Swedlo, 1974) and most of the remaining fine sediment is deposited to sinks in deeper water (Brunskill and Graham, 1979).

Erosional shorelines and shoreface profiles

Apart from the area of rapid transgression along the Netley Marsh shore (Penner and Swedlo, 1974; Nielsen and Conley, 1994), the most serious erosion problems appear to be associated with low cliffs in glaciolacustrine sediments of the former Lake Agassiz (Teller, 1976), exposed along the western shore of the South Basin. A detailed 1994 topographic survey (Fig. 18 of Forbes and Frobel, 1996) at site 8031 north of Gimli (line 31 of Penner and Swedlo, 1974) showed a 4 m cliff cut in rhythmically laminated Lake Agassiz silts and clays (Fig. 17), with a narrow sandy gravel beach at its base, giving way below lake level to a cobble frame and then to a veneer of sand over an erosional profile. A clay terrace was present at the base of the scarp. Cliff-top recession rates computed by overlaying the 1994 survey on a similar map by Penner and Swedlo (1974) ranged from <0.1 to 4.3 m/a (1971-1994), comparable to the long-term historical mean of about 2.3 m/a (1876-1971) and short-term rates of 3.6 to 4.6 m/a for the interval of rapidly rising lake level between 1961 and 1966 (Fig. 4).

Mapping of erosion rates in relation to observed outcrop of ice-contact deposits (till or basal glaciolacustrine facies), often manifested as boulder lags at headlands (Fig. 2), indicates a broad correlation between shoreline recession and lithology (Gelinas and Quigley, 1973). Erosion rates are somewhat lower at headlands associated with ice-contact material and somewhat higher in embayments where stratigraphically higher lacustrine silty clays are exposed in the shore zone.

Nearshore bathymetric and sub-bottom acoustic profiles obtained at numerous sites around the lake in 1996 reveal widespread evidence of shoreface erosion in relict Lake Agassiz clays. This corroborates earlier reports describing erosional surfaces in South Basin (Kushnir, 1971; Penner and Swedlo, 1974).

The approximate base of sand shown on the surveyed shore profile for site 8031 (Fig. 17) is based partly on borehole data in Penner and Swedlo (1974), showing <0.2 m of sand over clay, and partly on acoustic evidence for exposure of Agassiz Sequence deposits in 28 kHz sounding profiles across the inner shoreface in 1996. An Ekman grab recovered finely burrowed, planar-faceted, cubic, angular clasts of stiff clay, with granules and well rounded dolomite pebbles, from a depth of 3.3 m on this profile. A core taken through the ice in March 1997 penetrated 1.3 m of stiff clay in 2.6 m of water on the same shore-normal transect. Shallow cores recovered by Penner and Swedlo (1974) approximately 90 to 250 m out from the 1973 cliff line also showed exposures of firm clay at the lakebed. Cores obtained farther out (to 530 m) showed a range of materials from firm to very soft clay and a very thin pocket of poorly sorted sand (probably ice-rafted).

As demonstrated by Nielsen and Conley (1994), the south shore of the lake fronting Netley Marsh is a thin transgressive sand sheet, moving landward in a rollover fashion across the marsh surface, or spreading broad splays of washover sands through breaches in the low barrier. The washover origin is clearly apparent in the barrier profiles (Fig. 16 (line 8206)). In the southwest corner of the lake at Sans Souci (site 8219), 28 kHz acoustic profiles obtained during the 1996 nearshore survey (Fig. 19 of Forbes et al., this volume, b) reveal a thin wedge of sand extending lakeward over an erosional surface cut across Agassiz Sequence deposits (Todd and Lewis, 1996). Sidescan sonar imagery shows truncated Agassiz Sequence stratification with a patchy veneer of Lake Winnipeg mud near the inner limit of recent mud deposition (Fig. 20 of Forbes et al., this volume, b). A portion of the upper Agassiz Sequence appears to be slightly more resistant to erosion on the inner nearshore profile at Sans Souci, in depths of 2.0 to 2.5 m. The lakebed has an irregular morphology with local relief up to 0.25 m farther out the profile in water depths of 2.5 to 3.0 m.

Sections cut across Agassiz Sequence deposits were observed at several other sites along the western shore of the South Basin (e.g. off Gimli, north of Gimli, and along the northern shore of Willow Point, where local relief on the erosional surface included box-like depressions with vertical faces up to 1 m high). These appear similar to blocky lakebed morphology reported from Lake Vättern in Sweden (Norrman, 1964). Agassiz Sequence deposits were also observed on the lakebed south of Elk Island (Forbes et al., this volume, b).

Shoreface profiles off Grand Beach and Grand Marais were erosional but Agassiz Sequence deposits were not identified in these records. Lakebed material at these sites appeared to be gravel, till or other ice-contact material, consistent with the presence of morainal deposits onshore. Similar exposures of gravel lag material were noted off Balaton Beach, Drunken Point, Willow Point, and Matlock (Fig. 2) along the western shore. Fine gravel of beach origin, almost 0.5 m thick, was obtained by coring from the ice at a nearshore site south of Willow Point.

In the North Basin, acoustic profiles obtained off Berens Island, Marchand Point, George Island, Spider Islands, and Limestone Point all showed evidence of Agassiz Sequence sediments truncated at the lakebed (Forbes et al., this volume, b). As described earlier, coring from the ice off Disbrowe Point (near Berens River) confirmed the presence of stiff clay underlying silt and peat on the shoreface there.

The nearshore profile at Spider Islands (Figs 1 and 13) shows a smooth sand surface on the lakeward side of the nearshore bar, giving way (in about 5 m water depth) to an irregular erosional surface cutting across draped Agassiz Sequence sediments (Figs 14 and 18). These form a broad terrace with local relief of almost 1 m. Certain parts of the Upper Reflective Interval within the Agassiz Sequence (Todd et al., 1998) are clearly more resistant and stand out above the nearby lakebed. Farther out on the same profile, beyond a protruding outcrop of Precambrian rock, the erosional surface becomes extremely rough (Fig.14; Fig. 5 of Forbes et al., this volume, b), with local relief of 1.5 m or more. There is then an abrupt transition down profile to a contrasting smooth surface cutting across the Agassiz Sequence structures and sloping gently lakeward from 9 to 12 m depth and again (beyond another Precambrian outcrop) more steeply from 11 to 13 m (Fig. 14).

Other evidence for submergence

Beach sands on both flanks of the Pearson Reef Moraine (southeast of Hecla Island), buried under Lake Winnipeg mud, are documented by Todd et al. (1997, 1998; Forbes et al., this volume, b). These represent a shoreline about 13 m lower than present lake level approximately 4500 years ago.

Farther south in the basin, sand of possible littoral origin was recovered from a depth of 14 m below present lake level in *Namao* core 96900-224 (Lewis et al., this volume, a). An achene of *Scirpus* sp. (bulrush) with a radiocarbon age of 4040±70 years BP (CAMS-17434) was recovered from the same area in *Namao* core 94900-122 (Lewis and Todd, 1996b; Telka, this volume), approximately 14 m below present mean lake level. This sample is indicative of initial flooding by rising lake levels, approximately 30 km north of the present Netley Marsh shore between 4573 and 4413 cal BP. Although the shoreline at the time may have been north of the sampling location, this implies a long-term mean rate of southward transgression (shoreline retreat) of about 7 m/a over 4413 to 4573 years, corresponding to a rate of lake-level rise averaging 3.1 mm/a (0.31 m/century). In reality, rates are assumed to have varied over time as the South Basin water balance shifted from negative to overflowing (Lewis et al., 1998a, 1998b) and water level control was transferred progressively northward from a sill at the north end of the present South Basin to Warren Landing and then to Jenpeg at the north end of Playgreen Lake (Lewis and Todd, 1996a; Lewis et al., this volume, a).

Other data indicating submergence in South Basin include a 0.4 m unit of peat beneath 5 m of barrier sand and gravel south of Elk Island (Penner and Swedlo, 1974; Teller, 1980). The basal 0.1 m of this peat, including *Salix* sp., sedge, and *Scirpus* sp. macrofossils, from an elevation of about 214.6 m, produced a radiocarbon age of 1660±60 years BP (GSC-1977). The top 0.1 m yielded an age of 1060±210 radiocarbon years BP (GSC-1980). These data suggest a long-term mean rate of lake-level rise of about 1.8 mm/a (0.18 m/century), somewhat less than other data (the implication is that this peat may have formed above the main lake level, or the bulk peat dates may be too old). A core obtained through the ice in March 1997 at 4.4 m water depth in the same area (Forbes, in prep.) contained muddy peat from 0.03 to 0.10 m downcore, underlain by woody peat with clay-rich laminae, extending to the Agassiz Unconformity at 0.51 m downcore. AMS ages on seeds from this peat were 1800±60 radiocarbon years BP near the base (CAMS-44531, *Ranunculus scleratus* L.; Telka, this volume) and 1420±60 years BP near the top (CAMS-46194, *Bidens* sp.; Telka, this volume). With a calendar date between AD 426 and 801 (1524 to 1149 cal BP), this is a maximum age for submergence at 213.2 m elevation, 4.2 m below the long-term mean level of 217.4 m (Fig. 4). This suggests a rate of lake-level rise between 2.8 and 3.7 mm/a, with a best estimate of 3.2 mm/a (32 cm/century), somewhat higher than previously inferred at this site.

HIGHER RUNUP LEVELS

In contrast to the foregoing evidence for rising lake levels, other observations relate to a drop in runup limits. Mollusc specimens (*Lampsilis radiata siliquoidea* (Barnes)) from storm ridges at Netley Marsh and Willow Point produced unadjusted radiocarbon ages of 545±80 years BP (BGS-1947) and 775±105 years BP (BGS-1946). The corresponding runup levels range from about 1.5 to 2.0 m above present mean lake level. After appropriate adjustments for radiocarbon variance and reservoir effects, it appears that these shells may be modern, possibly representing storm-wave runup during the high water levels of the mid 1960s. On the other hand, the Willow Point storm ridge is a substantial deposit at an elevation well above present runup, dissected by washover passages of significant longshore extent. It is possible that this represents an interval of high mean lake level in the 19th Century or earlier.

High gravel berms with lichen growth are present on Selkirk, Berens, and Black Bear Islands in the North Basin (with partial tree cover on the latter two), attesting to one or more intervals of wave runup beyond the limit of recent activity.

DISCUSSION

Nielsen (1996, 1998, this volume) has reported on rooted stumps below present lake level in the South Basin, with calendar ages of AD 1640, 1655, 1670, 1675, and 1680. Similar trees at Spider Islands date from AD 1477 and 1656 (Nielsen, this volume). The broad consistency of this suite of dates from the 17th Century and earlier and the absence of dates from the 18th Century is intriguing, perhaps suggesting a basin-wide rise in lake level and associated die-off of low-lying trees. On the other hand, the error ranges for the calibrated ages, extending to the present in some cases, suggest the need for caution in interpreting these results. It is interesting to note that an interval of positive water balance (and presumably higher lake level) after AD 1600 has been inferred from charcoal accumulation rates and varve thickness in small lakes in Minnesota (Clark, 1990, 1993) and

Wisconsin (Gajewski et al., 1985). This implies a Little Ice Age regime of high Lake Winnipeg water levels; the implications for wind climate, setup statistics, and wave conditions are difficult to assess. However, it is reasonable to speculate that the variable growth structure at Limestone Point, changing beach alignment at Disbrowe Point, and geomorphic features elsewhere along the lakeshore (e.g. Fig. 3), may be related to climate and lake-level fluctuations at this time scale.

Other data, including erosional features in the northwest corner of the lake (McIntosh Reef trailing shoal and others), low beach ridges at the head of Limestone Bay, estuarine morphology of river mouths, submerged ridges of enigmatic origin in Limestone Bay, and transgressive barriers at Spider Islands, Limestone Point, along the western shore of North Basin, as well as farther south in the lake, also point to a basin-wide rise in lake level. This may relate to tilt control at Jenpeg (Lewis and Todd, 1996a; Lewis et al., this volume, a; Tackman et al., 1998), to addition of Saskatchewan River drainage about 4.7 ka (McMartin, 1996, this volume), or to lake-wide fluctuations in water balance of climatic origin (Nielsen, 1996; Lewis et al., 1998a, 1998b, this volume, a).

The smooth erosional profile on truncated Agassiz Sequence sediments at Spider Islands is highly suggestive of shoreface erosion. The present base of wave trimming at this site is estimated to be in the range of 6 to 8 m (Fig. 14), with smooth truncation limited to depths above 6 m. This implies water levels approximately 7 m lower than present at Spider Islands in order to create the lower part of the profile extending to at least 13 m present water depth.. Computations based on estimates of tilt as a function of age (Fig. 7 of Lewis and Todd, 1996a) suggest between 1.7 and 4.4 m water level rise since the lake control transferred to Jenpeg at 2.5 ka, leaving a further 2.6 to 5.3 m to be explained by earlier tilting over the 17 km projected distance to Warren Landing and by other mechanisms, such as addition of South Saskatchewan River discharge and climate change (Lewis et al., 1998b).

Aside from long-term shoreline recession driven by rising lake levels toward the south and southwest, rates of erosion may also fluctuate with lake-level variance at shorter time scales. Experience in the Great Lakes has demonstrated a strong correlation between rates of shoreline erosion and high water levels (e.g. Brown and Baird, 1980; Davidson-Arnott and Askin, 1980; Davidson-Arnott and Kreutzwiser, 1985; Kreutzwiser, 1988; Rasid et al., 1989; Folger et al., 1994; Amin and Davidson-Arnott, 1995; Angel, 1995). The range of mean annual water levels on Lake Winnipeg is almost 2 m and relatively high erosion rates have been reported for periods of rising lake levels (Penner and Swedlo, 1974). Higher water levels lead to a reduction in the width of protective beaches, allow waves to attack higher up the profile, and allow a larger proportion of wave energy to reach the shore and attack the bluff toe. Removal of material at the base or toe of a coastal cliff is a major contributor to erosion and coastal retreat (Robinson, 1977; Sunamura, 1983), particularly in cohesive tills and lacustrine muds. Such erosion can be especially severe at times of high water level (Amin and Davidson-Arnott, 1995).

The limited beach volumes (Penner and Swedlo, 1974) and the widespread erosion of Agassiz clay on the shoreface, particularly along the western lakeshore, suggest that shoreline retreat may occur independent of lake-level change (cf. Pope et al., 1993). The sand and gravel content of Lake Agassiz sediments is generally low. Last (1996) reported textural data from *Namao* 94900 cores, including 187 samples of Agassiz Sequence deposits (identified from core logs in Lewis and Todd, 1996b). The mean sand content was 3.15±0.37% (standard error). Most samples had no sand or gravel and the largest value was 22%. These data, consistent with results from 1996 core sample reported in this volume (Lewis et al., this volume, b; Forbes, Appendix 10.7, this volume), imply that more than 96% of material removed by erosion of shoreface Agassiz Sequence exposures is mud. This fine fraction will be removed to deep water (contributing to Winnipeg Sequence muds). Only a small proportion of eroded sediment will be available for natural beach nourishment and shore protection. Furthermore, the fractured structure of the Agassiz clays, resulting from several thousand years of subaerial exposure at present shoreface sites in the south, suggests that these muds may be eroded by wave pressure plucking as well as by direct shear, sand abrasion (Kamphuis, 1983, 1987), or sand saltation impacts (Amos et al., 1998). This is consistent with the irregular and blocky surface observed at many sites, suggesting large local heterogeneity in the erosion process. The role of intermittent softening, as observed in Lake Ontario (Davidson-Arnott and Ollerhead, 1995) has not been assessed in Lake Winnipeg. The present rates of erosion across the shoreface are unknown at present, but high rates of shore recession suggest that it is occurring and may be a dominant mechanism for shoreline retreat.

CONCLUSIONS

Lake Winnipeg is the largest of Manitoba's Great Lakes, with a wide diversity of shoreline geomorphology. Spits and barrier beaches are common landforms around the entire perimeter of

Lake Winnipeg. These depositional shore features display a variety of scale, morphology, and geomorphic history, products of varying rates of sediment supply, lake-level change, and shoreline migration in locations with a wide range of exposure, fetch, and resulting wave climate.

Prograded beach-ridge complexes at several locations in the lake, most commonly in the North Basin, reflect accumulation of longshore-derived sediment in headland-confined embayments. In the North Basin, a 20 km long recurve spit has developed at Limestone Point, fed by longshore transport of sediments from eroding north shore cliffs cut into fine-grained deposits of the Hargrave Moraine. This shore lies close to the northern lake outlet and has been less affected by northeastward isostatic tilting than most other parts of the lakeshore. Three distinct groups of recurve ridges on the spit suggest an episodic history of water levels, wave energy, and shore-zone sediment transport over the past 500 to 1500 years.

A large-scale spit-like structure at Disbrowe Point near Berens River, in the southeastern North Basin, is interpreted instead as a reworked remnant of a breached transgressive barrier complex that may have extended southwest toward Berens Island. Recurved beach ridges truncated by the present shoreline on the south side of Gull Bay appear to have originated by southward growth of a spit from the north. Breaching of this spit in its proximal or cental section led to the present opposing North and South Bar remnant spits.

Many barriers, particularly in the central and southern parts of the lake, show evidence of long-term onshore migration by washover and localised breaching. Other geomorphic indicators of shoreline retreat (gravel retreat shoals, beach-ridge truncation, landward dune migration, marsh expansion, active cliff erosion) attest to ongoing shore-zone recession, largely driven by rising lake levels. These are attributed in part to southwestward isostatic tilting, manifested by transgressive shore structures at the south ends of major bays and the South Basin, and in part to climate change and river diversion.

Analysis of long-term shoreline retreat along the western shore of the South Basin demonstrates a correlation between erosion rates and the lithology of materials in the shore zone. Erosional shoreface profiles cut into glaciolacustrine deposits of Lake Agassiz are common throughout the lake, suggesting that shoreline erosion is partly driven by downcutting in the nearshore, with insufficient sand supply to build an equilibrium profile.

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FIGURES

Figure 1. Lake Winnipeg shoreline, showing major rivers, key place names, and locations of shore-zone surveys undertaken as part of this project.

Figure 2. South Basin shoreline showing 1996 survey sites, locations discussed in text, and generalised rates of shoreline recession prior to the mid-1970s (after Penner and Swedlo, 1974).

Figure 3. Oblique air photo looking southwest across the southern spit (South Bar) and associated beach-ridge complex at Gull Bay on the western shore of the North Basin south of Long Point (Fig. 1). Note truncation of recurved beach ridges at the present shoreline. These ridges were built toward the south (away from camera) whereas present South Bar spit is aligned in opposing direction (toward camera). DLF/1994/09/09 (FZ9436-15).

Figure 4. Lake Winnipeg water levels from 1914 to 1995 inclusive (Berens River data courtesy Water Survey of Canada).

Figure 5. Oblique air photo showing lag shoal headland at Morass Point, with wooded beach ridges at the downdrift end of the north-side (updrift) barrier, western shore of North Basin opposite Reindeer Island (see Fig. 1 for location) (Fig. 6a of Forbes and Frobel, 1996). DLF/1994/09/09 (FZ9436-38).

Figure 6. South end of North Basin, showing barrier and fringing barrier shoreline along north shore of Berens Island; Berens Bank; and Disbrowe Point, with east shore of lake north to McKay Point. Also shown are locations of CCGS *Namao* grab samples 210 and 211. Associated sidescan sonar record at sampling site (Forbes et al., this volume) shows erosional clay surface typical of nearshore sites at many locations around the lakeshore.

Figure 7. Vertical air photo showing recurved ridges at the distal end of Limestone Point spit, trailing shoal behind McIntosh Reef, and tombolo platform with ridge-and-runnel bar structures building lakeward behind the shoal. Part of A24996-52 (1976).

Figure 8. Limestone Point showing spit structures and growth segments, beach-ridge complex at the head of Limestone Bay, and location of core and profile at GSC site 8200 (Fig. 7; Forbes and Frobel, 1996).

Figure 9. Beach-ridge complex and marsh at head of Limestone Bay, in embayment formed by the growth of Limestone Point. Lake Winnipeg shore (GSC site 8200 in foreground) consists of a transgressive fringing sandy barrier and foredune ridge, truncating the bayhead beach-ridge sequence (Fig. 12c of Forbes and Frobel, 1996). DLF/1994/09/08 (FZ9431-16).

Figure 10. Oblique air photos showing central part of barrier beach at Grand Beach. Top: parabolic dunes migrating landward over backbarrier flats (including parking lot in background). Bottom: 'Tidal' inlet with well-developed flood delta (background) and 'low-tide' terrace (foreground). DLF/1994/09/07 (FZ9423-01 and -03).

Figure 11. Oblique air photo looking north over the distal end of Disbrowe Point, with the narrow neck in the distance (Fig. 11c of Forbes and Frobel, 1996). DLF/ 994/09/08 (Z9429-33).

Figure 12. Map showing Disbrowe Point shoreline, shoal to the west, and nearshore bathymetry, based on 1934 surveys (after CHS, 1935), 1996 shoreline survey and beach-ridge morphology from 1950s air photo.

Figure 13.	Vertical air photo mosaic (parts of A22755-12 and -28, 1971) showing Spider Islands barrier and estuarine mouth of Bélanger River (with prograded beach ridges). Line of profile (Fig. 14) and ground surveys on spit are also indicated. GSC-320 and GSC-321 are survey control points.
Figure 14.	Surveyed bathymetric and topographic profile across shoreface, nearshore, beach and dunes at Spider Islands, August 1996. See Figure 13 for location. Stippled area shows extent of Fig. 18.
Figure 15.	South end of South Basin, showing generalized bathymetry and locations of shore surveys.
Figure 16.	Surveyed shore profiles at sites 8206 to 8210, 8212, and 8217, Netley Marsh shore (from Forbes and Frobel, 1996). See Fig. 15 for locations. Lake to right with approximate water level at time of surveys. Vertical exaggeration ~8.9x.
Figure 17.	Surveyed 1994 shore profile at site 8031, showing approximate location of cliff in 1973 (the latter after data in Penner and Swedlo, 1974).
Figure 18.	Knudsen 320M subbottom (28 kHz) profile across inner shoreface and nearshore at Spider Islands (see Figs. 13 and 14 for location).

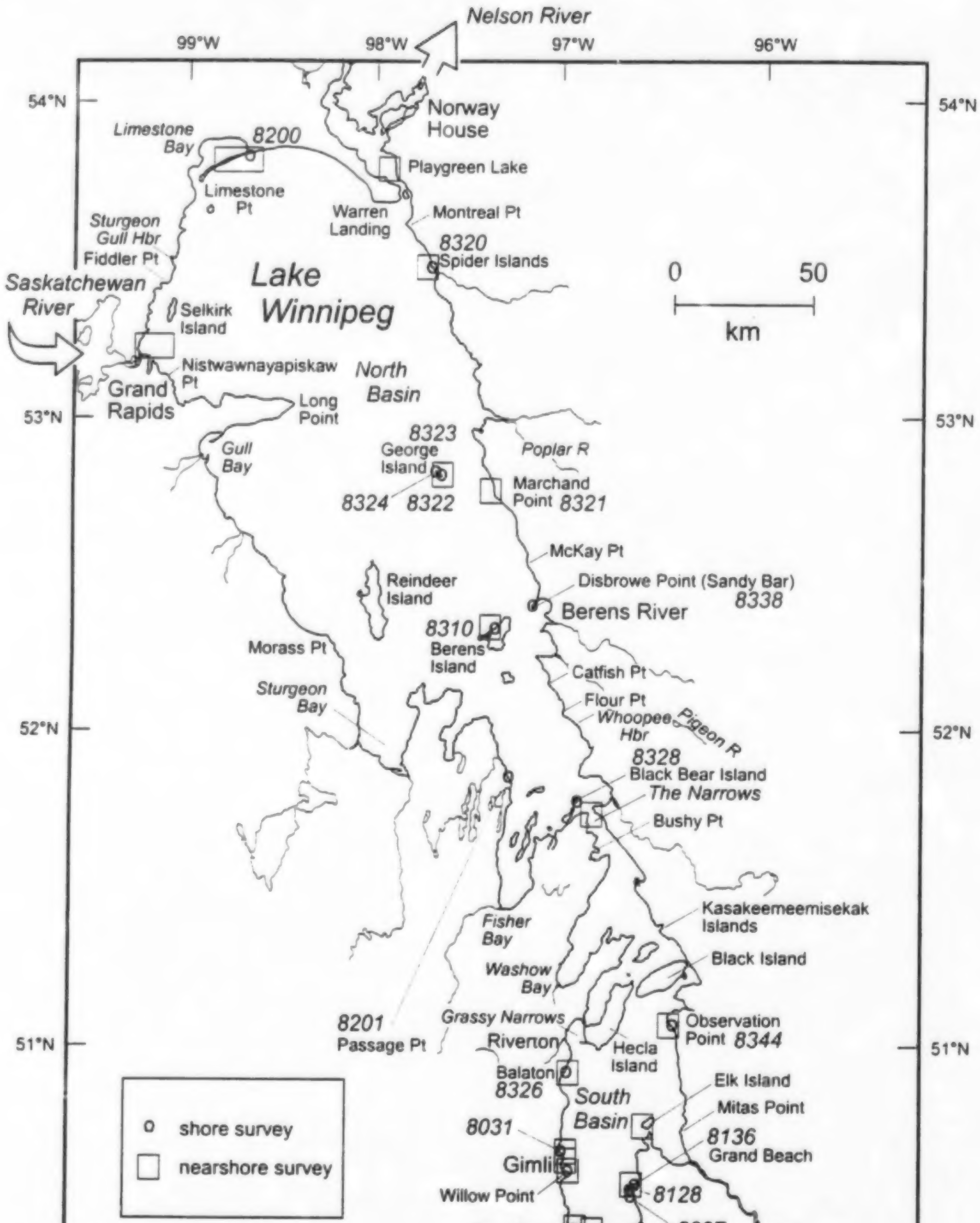

Nelson River
99°W
98°W
97°W
96°W
54°N
54°N
Norway House
Limestone Bay
8200
Playgreen Lake
Limestone Pt
Warren Landing
Montreal Pt
Sturgeon Gull Hbr
8320
Spider Islands
Fiddler Pt
Lake Winnipeg
0
50
km
Saskatchewan River
Selkirk Island
Nistwawnayapiskaw Pt
North Basin
Grand Rapids
Long Point
53°N
53°N
8323
George Island
Poplar R
Gull Bay
Marchand Point 8321
8324
8322
McKay Pt
Reindeer Island
Disbrowe Point (Sandy Bar)
8338
Berens River
8310
Berens Island
Morass Pt
Catfish Pt
Sturgeon Bay
Flour Pt
Whoopee Hbr
Pigeon R
52°N
52°N
8328
Black Bear Island
The Narrows
Bushy Pt
Kasakeemeemisekak Islands
Fisher Bay
Black Island
Washow Bay
8201
Passage Pt
Grassy Narrows
Riverton
Observation Point 8344
51°N
51°N
Hecla Island
Balaton
8326
Elk Island
South Basin
Mitas Point
shore survey
nearshore survey
8031
8136
Grand Beach
Gimli
8128
Willow Point
8327
Sans Souci
8206 -8219
Netley Marsh
Winnipeg River
99°W
98°W
Red River
96°W

Figure 1. Lake Winnipeg shoreline, showing major rivers, key place names, and locations of shore-zone surveys undertaken as part of this project.

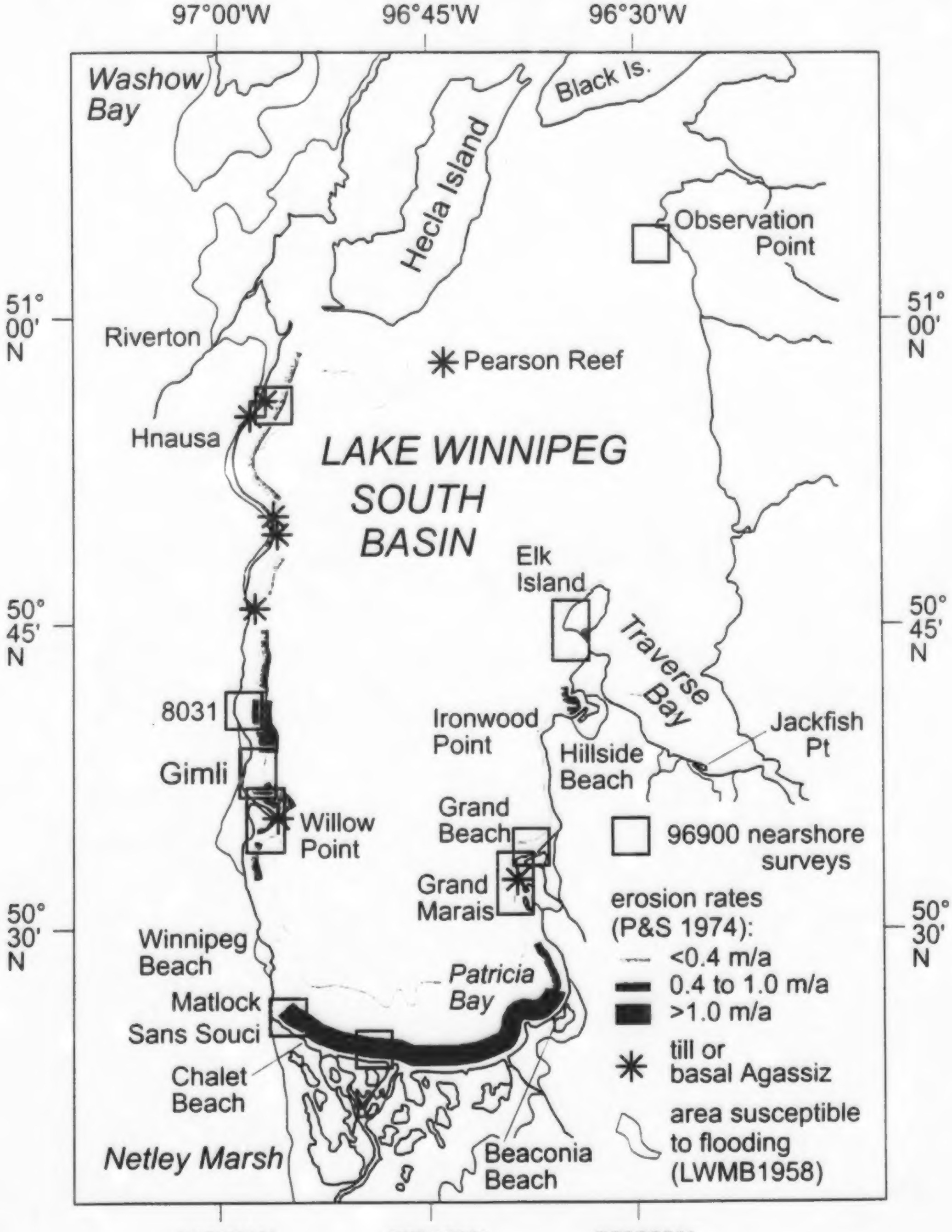

97°00'W
96°45'W
96°30'W
Washow Bay
Black Is.
Hecla Island
Observation Point
51° 00' N
Riverton
Pearson Reef
Hnausa
LAKE WINNIPEG SOUTH BASIN
Elk Island
50° 45' N
Traverse Bay
8031
Ironwood Point
Jackfish Pt
Hillside Beach
Gimli
Willow Point
Grand Beach
Grand Marais
96900 nearshore surveys
erosion rates (P&S 1974):
<0.4 m/a
0.4 to 1.0 m/a
>1.0 m/a
50° 30' N
Winnipeg Beach
Patricia Bay
Matlock
Sans Souci
Chalet Beach
till or basal Agassiz
area susceptible to flooding (LWMB1958)
Netley Marsh
Beaconia Beach

Figure 2. South Basin shoreline showing 1996 survey sites, locations discussed in text, and generalised rates of shoreline recession prior to the mid-1970s (after Penner and Swedlo, 1974).

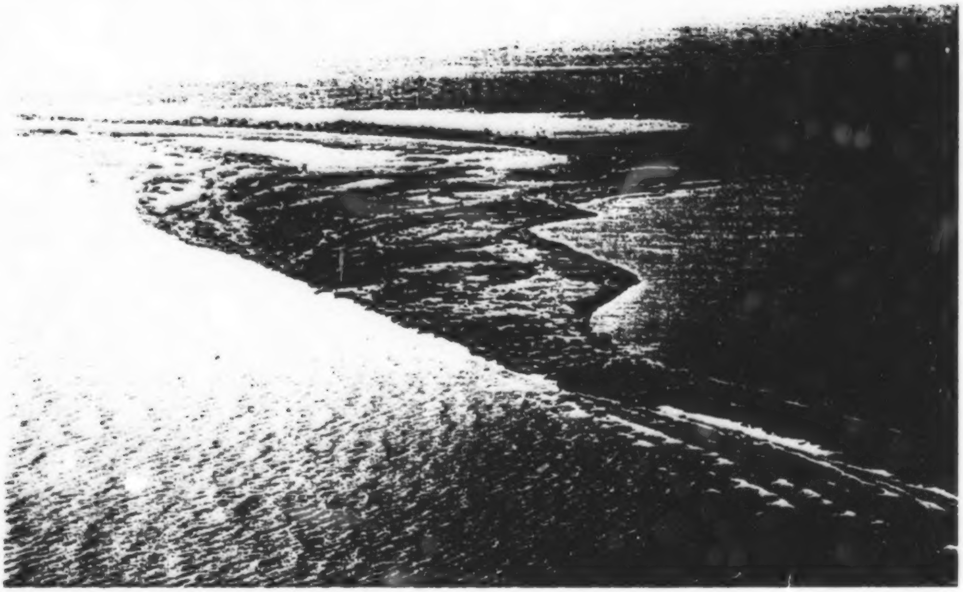


Figure 3. Oblique air photograph looking southwest across the southern spit (South Bar) and associated beach-ridge complex at Gull Bay on the western shore of the North Basin south of Long Point (Fig. 1). Note truncation of recurved beach ridges at the present shoreline. These ridges were built toward the south (away from camera) whereas present South Bar spit is aligned in opposing direction (toward camera). DLF/ 1994/09/09 (FZ9436-15).

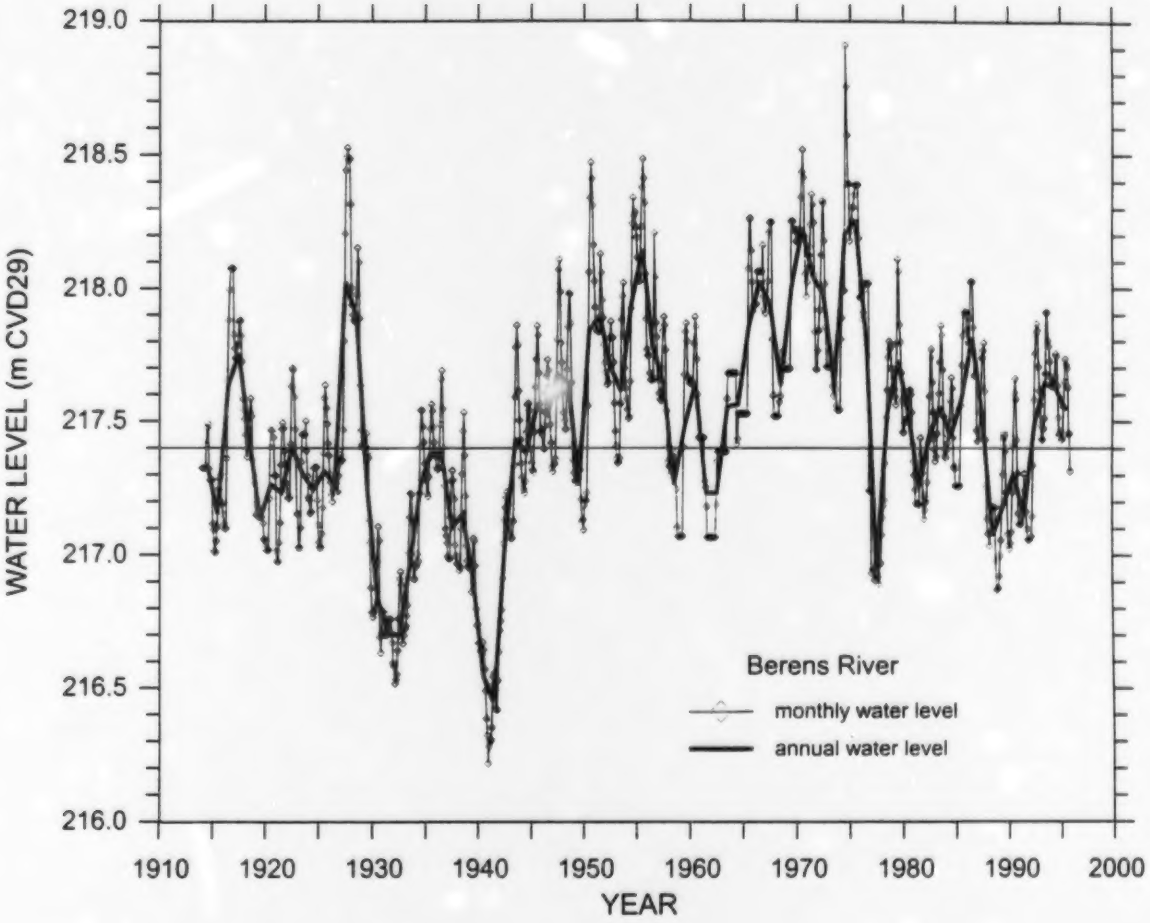


Figure 4. Lake Winnipeg water levels from 1914 to 1995 inclusive (Berens River data courtesy Water Survey of Canada).

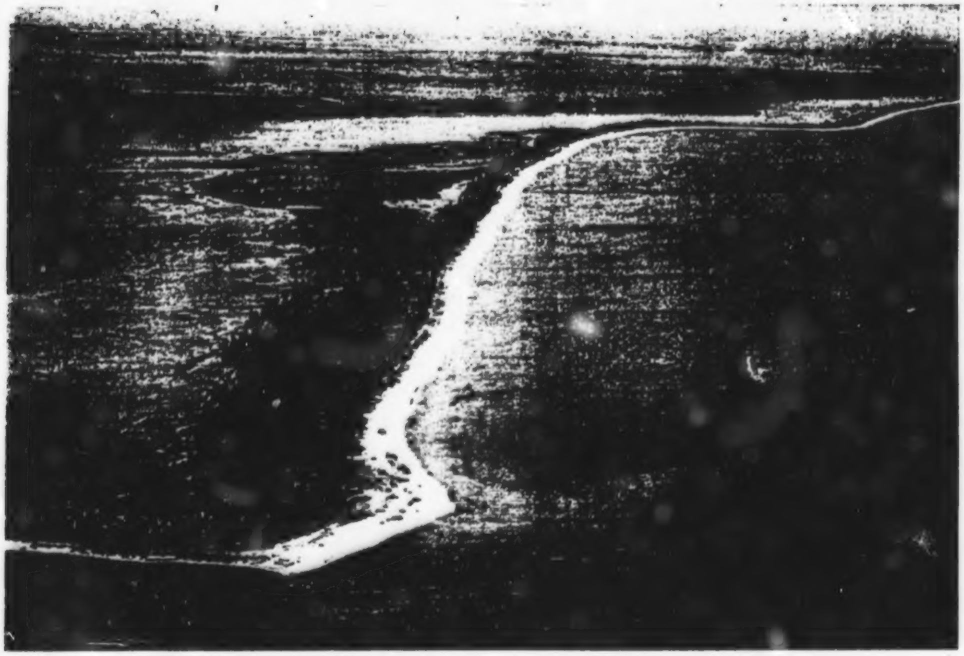


Figure 5. Oblique air photograph showing lag shoal headland at Morass Point, with wooded beach ridges at the downdrift end of the north-side (updrift) barrier, western shore of North Basin opposite Reindeer Island (see Fig. 1 for location). DLF/ 1994/09/09 (FZ9436-38).

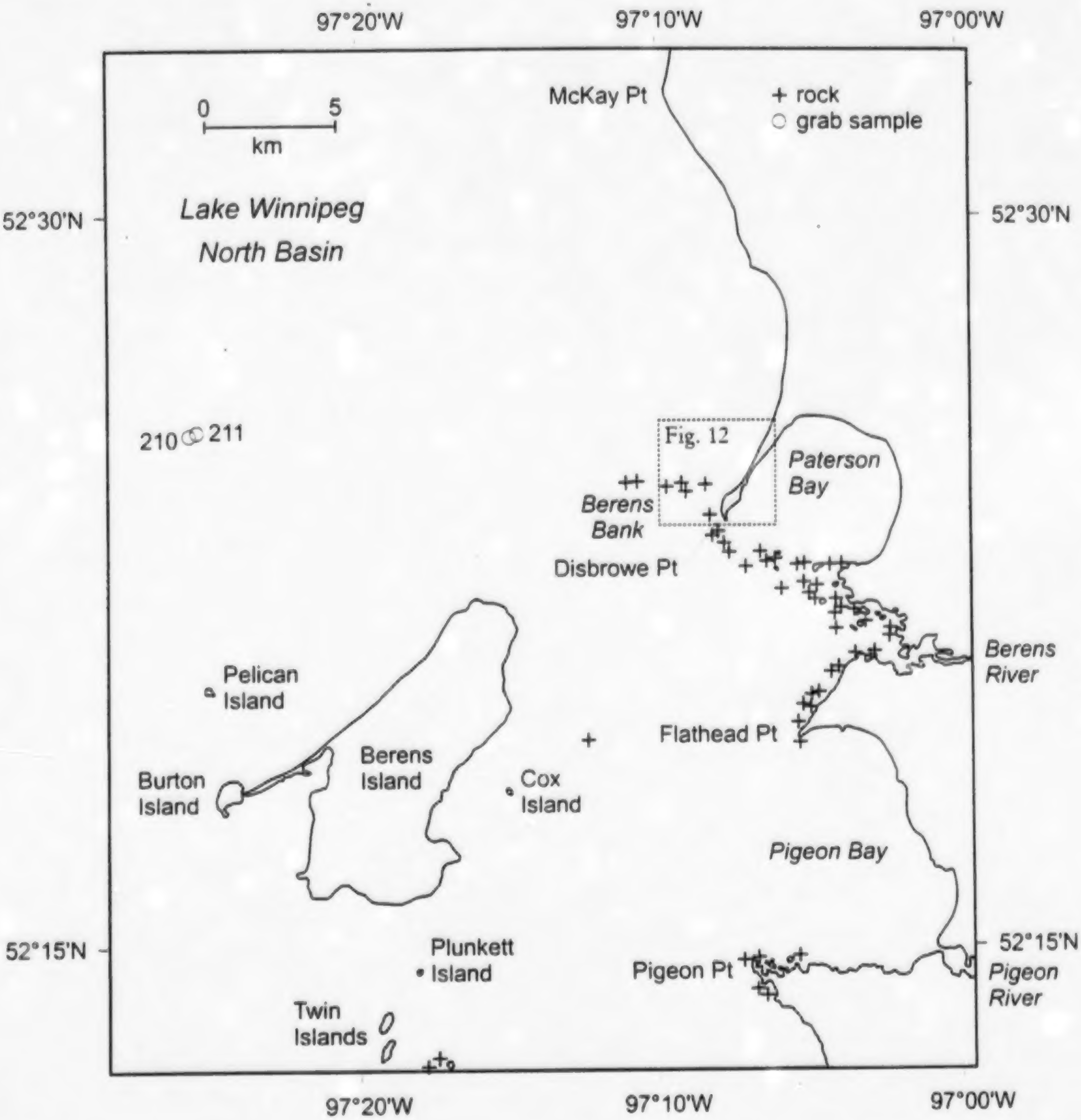

97°20'W
97°10'W
97°00'W
McKay Pt
+ rock
○ grab sample
0
5
km
52°30'N
52°30'N
Lake Winnipeg
North Basin
210
211
Fig. 12
Paterson Bay
Berens Bank
Disbrowe Pt
Berens River
Pelican Island
Flathead Pt
Berens Island
Burton Island
Cox Island
Pigeon Bay
52°15'N
52°15'N
Plunkett Island
Pigeon Pt
Pigeon River
Twin Islands
97°20'W
97°10'W
97°00'W

Figure 6. South end of North Basin, showing barrier and fringing barrier shoreline along north shore of Berens Island; also Berens Bank and Disbrowe Point, with east shore of lake north to McKay Point. Also shown are locations of CCGS *Namao* grab samples 210 and 211. Associated sidescan sonar record at sampling site (Forbes et al., this volume) shows erosional clay surface typical of nearshore sites at many locations around the lake.

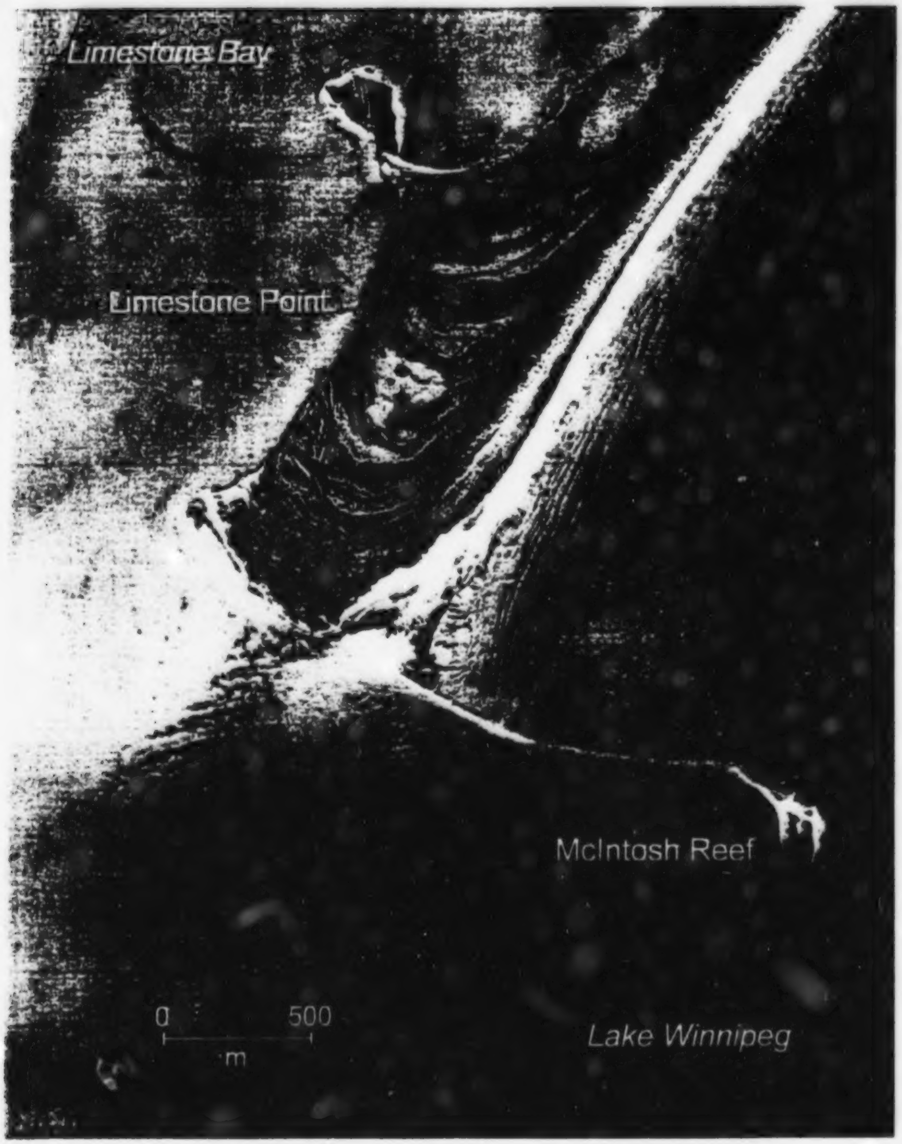

Limestone Bay
Limestone Point
McIntosh Reef
0
500
m
Lake Winnipeg

Figure 7. Vertical air photograph showing recurved ridges at the distal end of Limestone Point spit, trailing shoal behind McIntosh Reef, and tombolo platform with ridge-and-runnel bar structures building lakeward behind the shoal. Part of A24996-52 (1976).

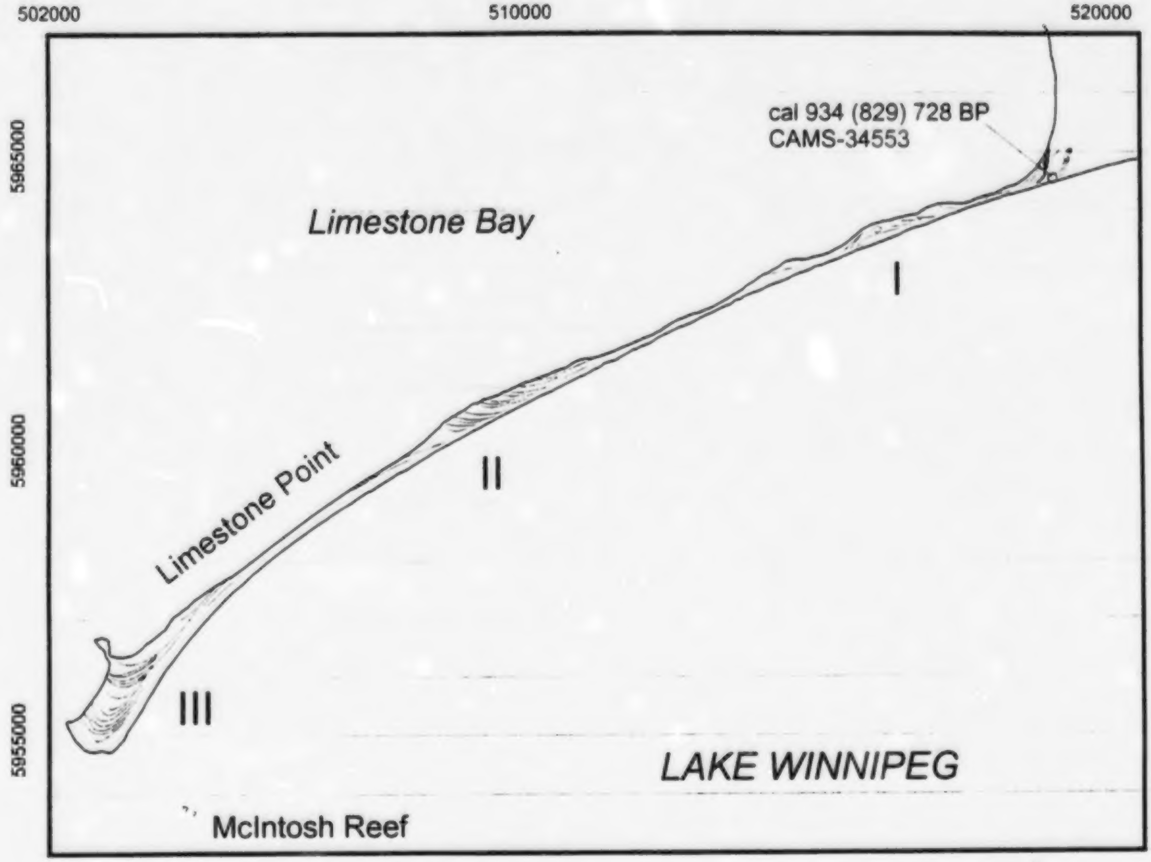

502000
510000
520000
5965000
5960000
5955000
cal 934 (829) 728 BP
CAMS-34553
Limestone Bay
I
II
Limestone Point
III
LAKE WINNIPEG
McIntosh Reef

Figure 8. Limestone Point showing spit structures and growth segments, beach-ridge complex at the head of Limestone Bay, and location of core and profile at site 8200 (Fig. 7; Forbes and Frobel, 1996).

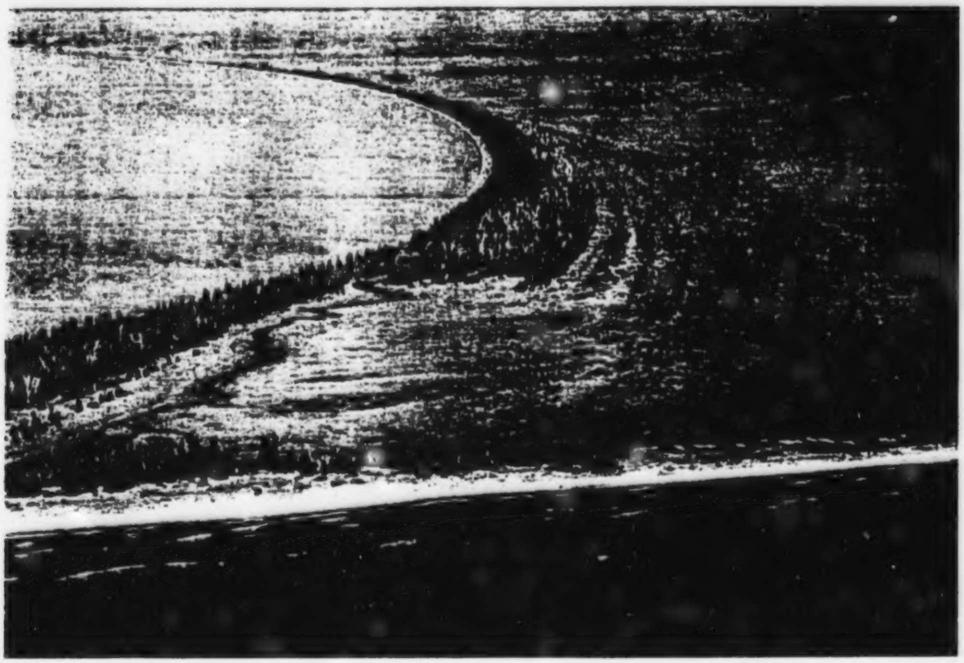
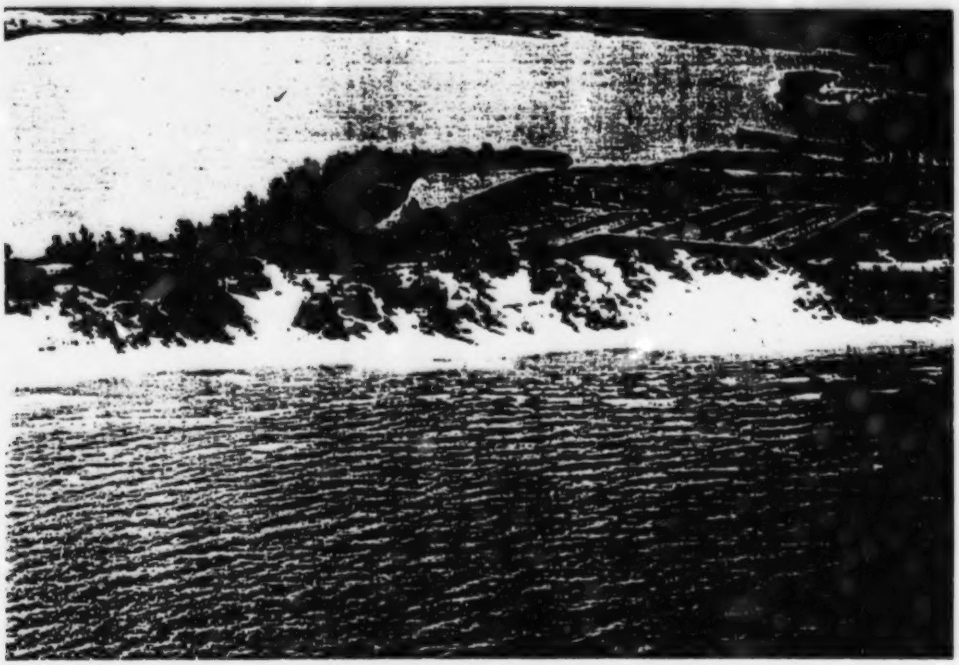


Figure 9. Beach-ridge complex and marsh at head of Limestone Bay, in embayment formed by the growth of Limestone Point. Lake Winnipeg shore (site 8200 in foreground) consists of a transgressive fringing sandy barrier and foredune ridge, truncating the bayhead beach-ridge sequence behind. DLF/ 1994/09/08 (FZ9431-16).



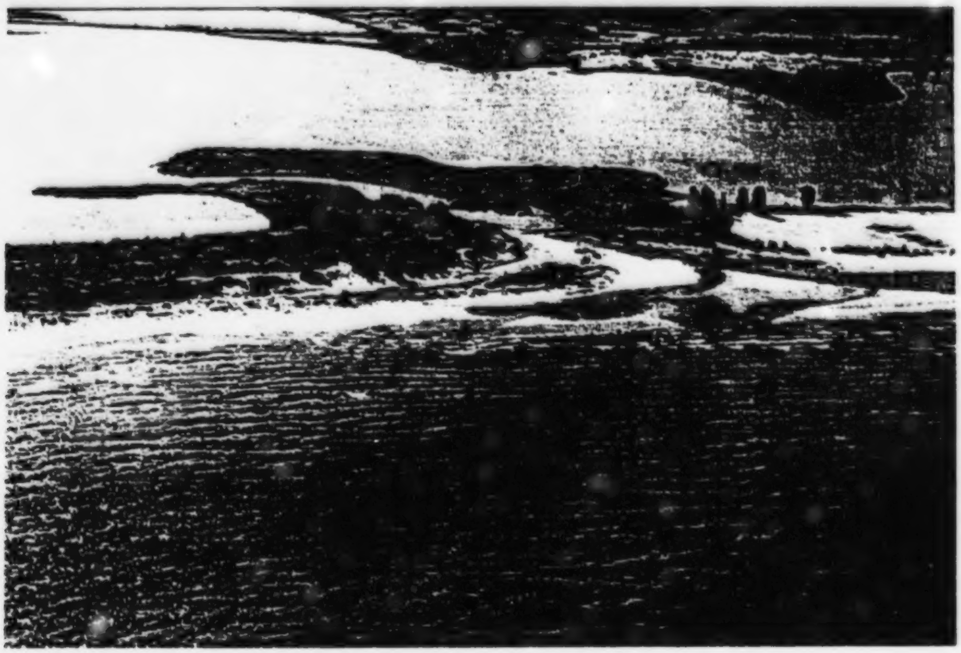


Figure 10. Oblique air photographs showing central part of barrier at Grand Beach, eastern shore of South Basin (see Fig. 2 for location). Top: Parabolic dunes migrating landward over backbarrier flats (including parking lot in background). Bottom: 'Tidal' inlet with well developed 'flood delta' in background and 'low-tide terrace' in foreground. DLF/ 1994/09/07 (FZ9423-01 & -03).

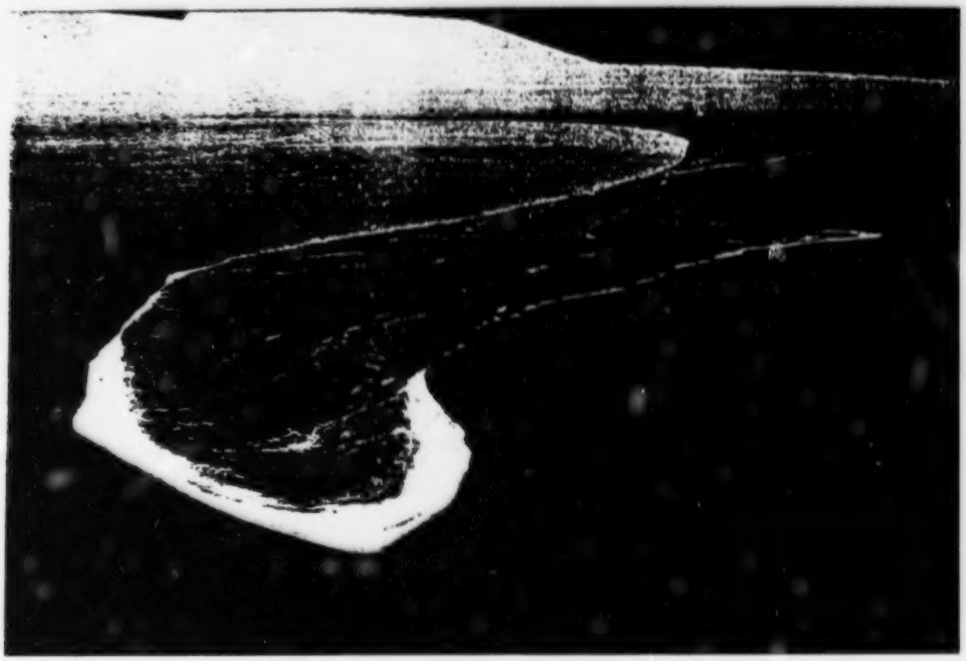


Figure 11. Oblique air photograph looking north over the distal end of Disbrowe Point, with the narrow neck in the distance. DLF/ 1994/09/08 (FZ9429-33).

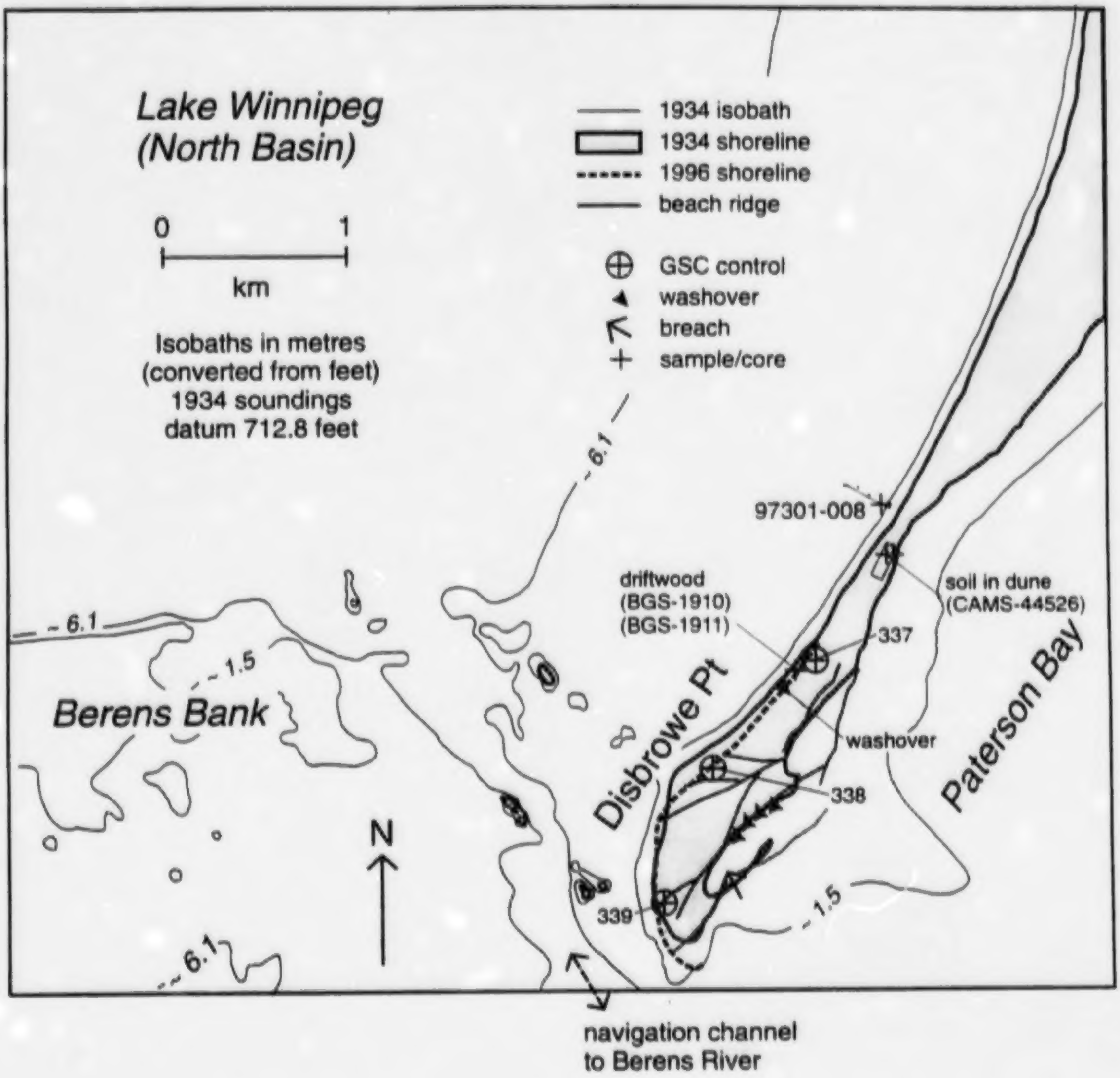

Lake Winnipeg (North Basin)
0
1
km
Isobaths in metres (converted from feet) 1934 soundings datum 712.8 feet
1934 isobath
1934 shoreline
1996 shoreline
beach ridge
GSC control
washover
breach
sample/core
6.1
1.5
Berens Bank
N
97301-008
driftwood (BGS-1910) (BGS-1911)
soil in dune (CAMS-44526)
337
338
339
washover
Disbrowe Pt
Paterson Bay
navigation channel to Berens River

Figure 12. Map showing Disbrowe Point shoreline, shoal to the west, and nearshore bathymetry, all based on 1934 surveys (after CHS, 1935). Also shows beach-ridge morphology from 1950s aerial photography, 1996 shoreline based on surveys for this project, locations of radiocarbon dated samples from 1996 and 1997, and position of 1997 nearshore core (97301-008).

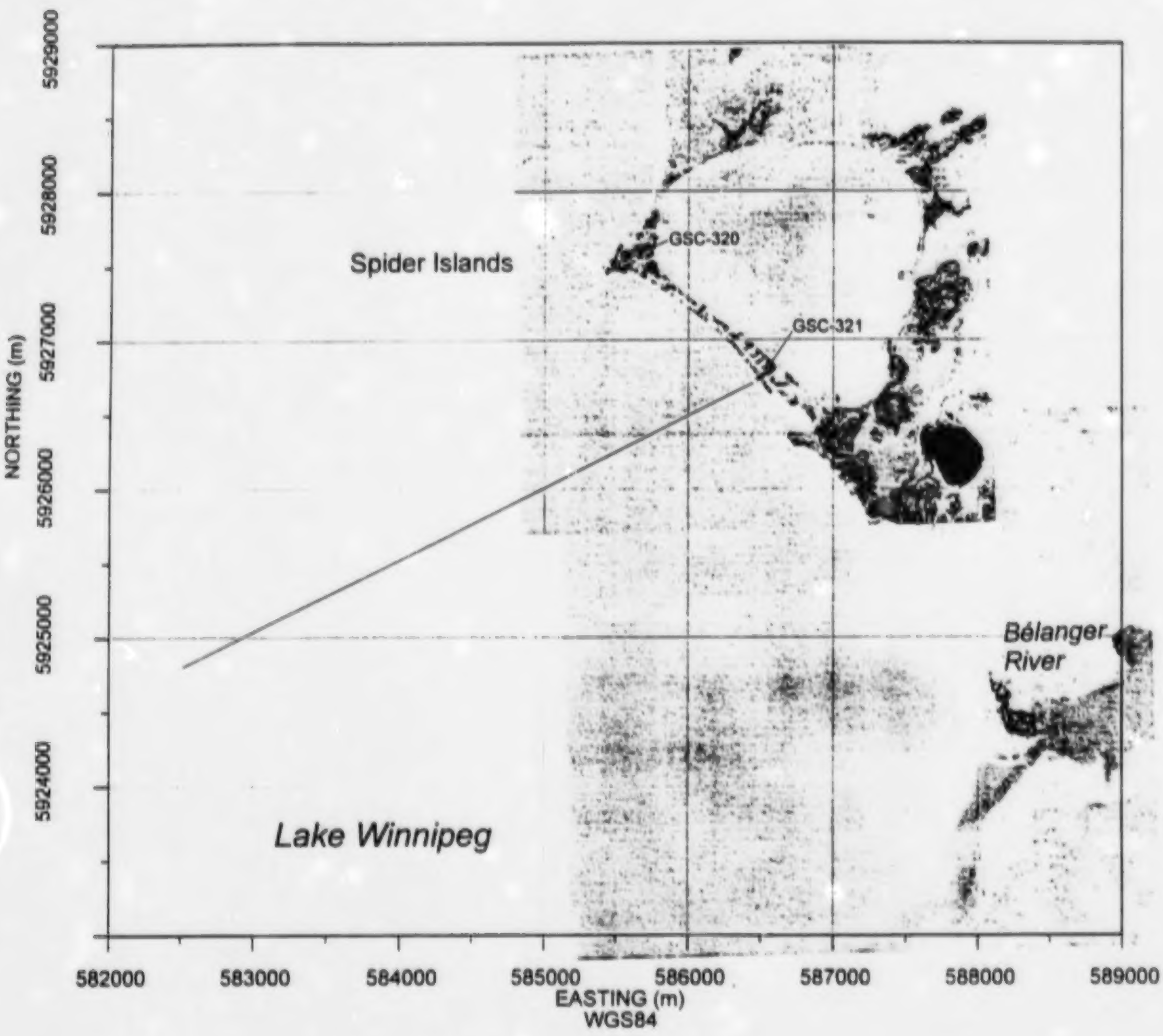

NORTHING (m)
5929000
5928000
5927000
5926000
5925000
5924000
Spider Islands
GSC-320
GSC-321
Bélanger River
Lake Winnipeg
582000
583000
584000
585000
586000
587000
588000
589000
EASTING (m)
WGS84

Figure 13. Vertical airphoto mosaic (parts of A22755-12 and -28, 1971) showing Spider Islands barrier and estuarine mouth of Bélanger River (with prograded beach ridges). Line of profile (Fig. 14) and ground surveys on beach and dunes are also indicated. GSC-320 and GSC-321 are survey control points.

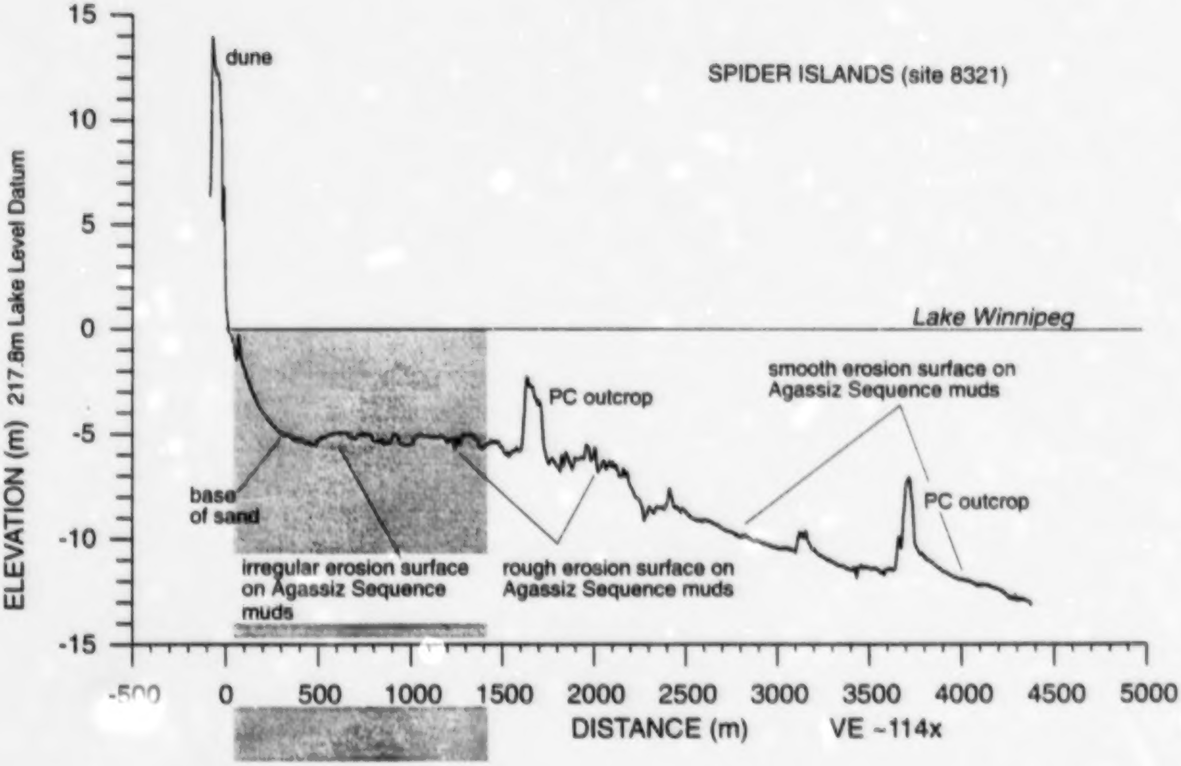
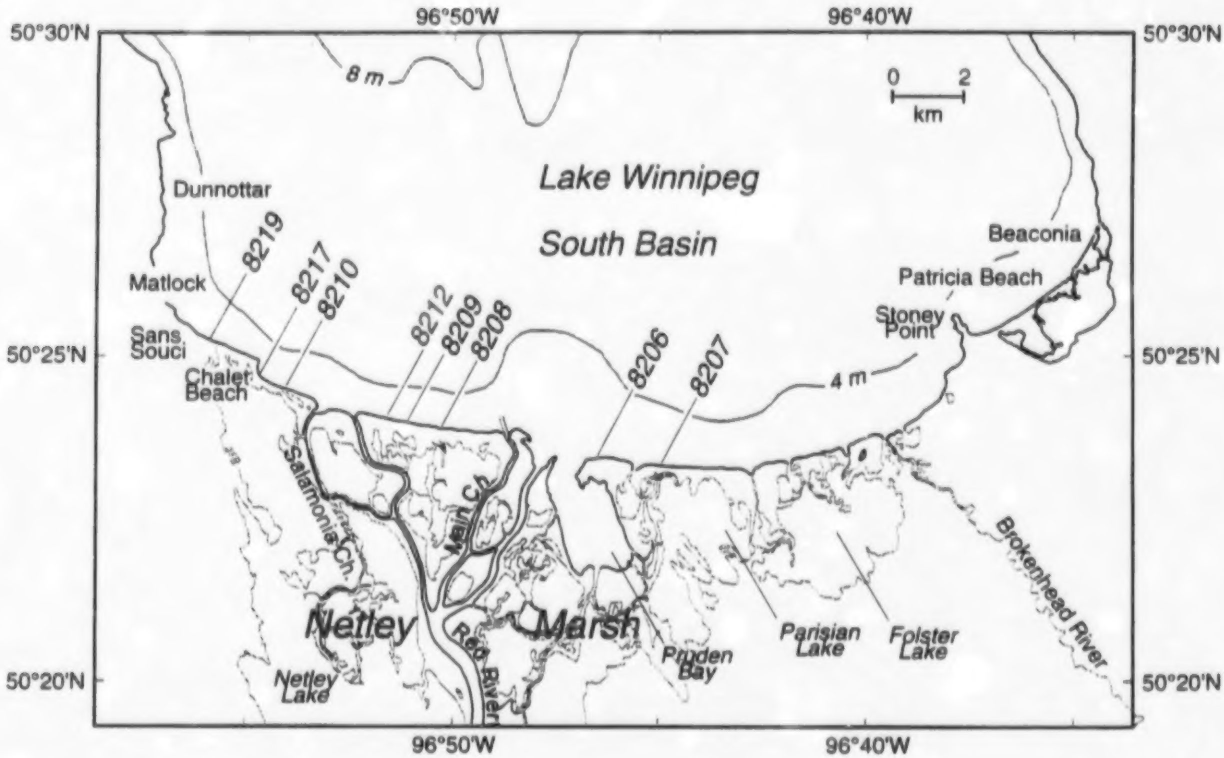


Figure 14. Surveyed bathymetric and topographic profile across shoreface, nearshore, beach and dunes at Spider Islands, August 1996. See Fig. 13 for location. Stippled area shows extent of Fig. 18.



50°30'N
96°50'W
96°40'W
50°30'N
8 m
0
2
km
Lake Winnipeg
South Basin
Dunnottar
Matlock
Sans Souci
Chalet Beach
8219
8217
8210
8212
8209
8208
8206
8207
4 m
Beaconia
Patricia Beach
Stoney Point
50°25'N
50°25'N
Salamonia Ch.
Main Ch.
Netley
Marsh
Red River
Netley Lake
Pruden Bay
Parisian Lake
Folster Lake
Brokenhead River
50°20'N
50°20'N
96°50'W
96°40'W

Figure 15. South end of South Basin, showing bathymetry and locations of shore surveys (after Forbes and Frobel, 1996).

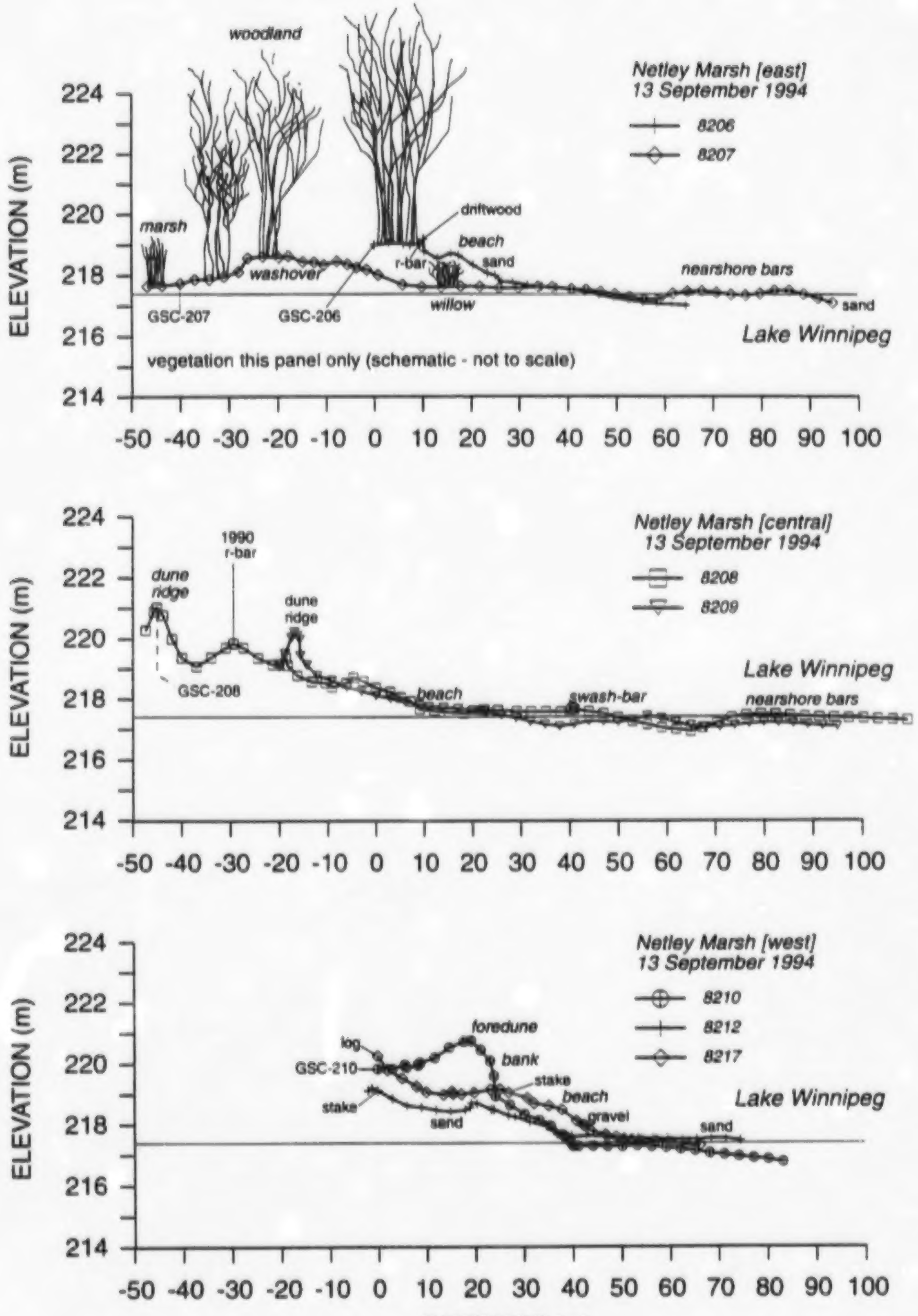


Figure 16. Surveyed shore profiles at sites 8206 to 8210, 8212, and 8217, Netley Marsh shore of South Basin (after Forbes and Frobel, 1996). See Fig. 15 for locations. Lake to right with approximate water level at time of surveys. Vertical exaggeration ~8.9x.

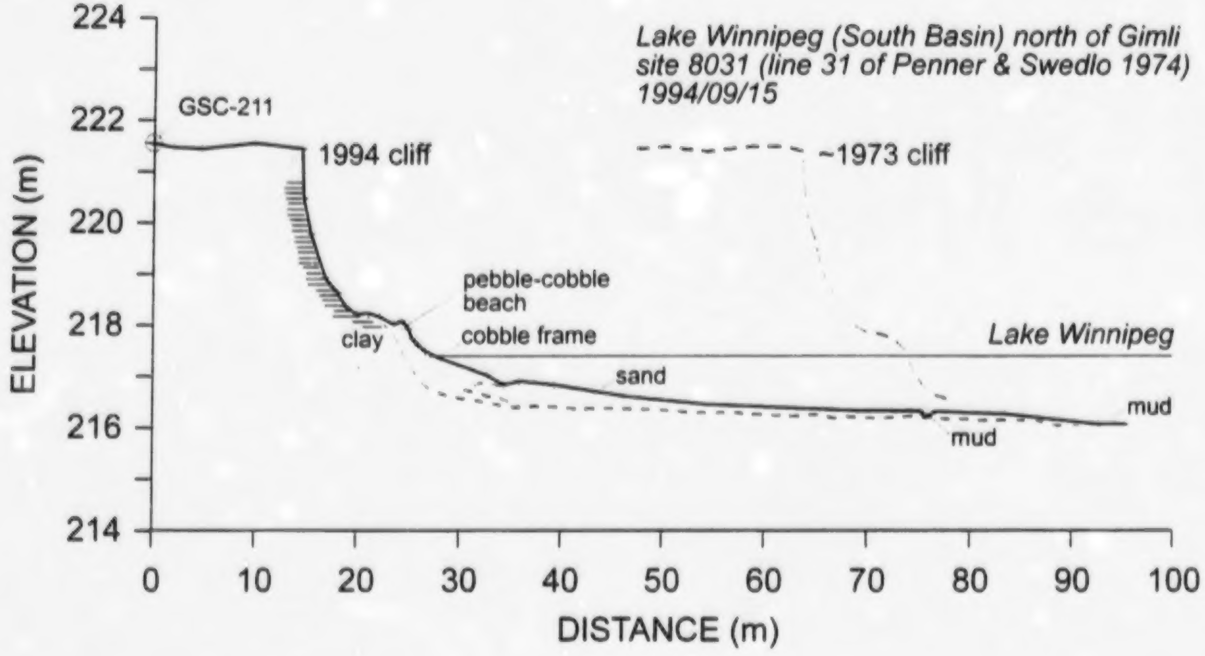


Figure 17. Surveyed cliff and shore profile at site 8031 in 1994, showing approximate location of cliff in 1973 (the latter after Penner and Swedlo, 1974) and estimated base of beach gravel and nearshore sand.

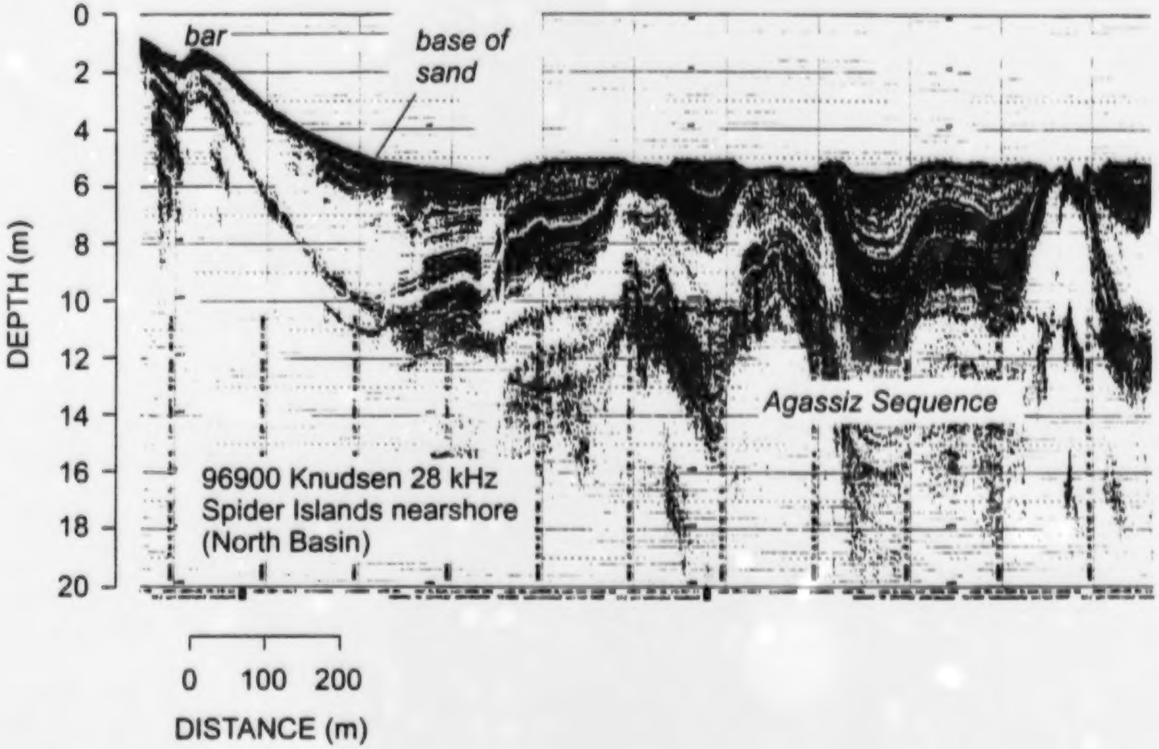


Figure 18. 28 kHz bathymetric and subbottom profile across inner shoreface and nearshore at Spider Islands in August 1996 (see Figs 13 and 14 for location).

9.6 Effects of inundation stress on tamarack (*Larix laricina*): Implications for use of trees in monitoring lake-level rise

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INTRODUCTION

Radiocarbon age determinations or dendrochronological dating of submerged or partly submerged tree stumps, preserved in growth position, have been used by numerous workers to investigate water-level changes driven by both tectonic movements of the earth's crust and climatic fluctuations (Grant, 1970, 1980; Heyworth, 1978; Atwater and Yamaguchi, 1991; Jacoby et al., 1997). Knowing the age, initial and final elevations of a stump relative to water level permits an estimate of the rate of change in the elevation of the earth's crust or the level of the water table to be made. These studies are based on the tacit assumption that the trees grew in sites where the water table was below the roots but close to the level at which mortality occurred. Although a survey of the lowest elevation of living trees provides constraints there may be other factors which limit this approach (Nielsen and Conley, 1994). In cases where the age differences, tectonic movements or climatic fluctuations are large, the uncertainty in the estimate of the paleowater level may mean the difference of only a few centimetres in the resulting reconstruction and may thus be ignored. In high resolution studies, or where fluctuations are small, a more precise estimate of the maximum possible elevation of the paleowater table may be required (Nielsen, 1998). However, growth and survival in forest tree species are dependent on many factors in the physical environment. Every species has certain essential requirements and grow within a limited range of environmental conditions. These conditions, including the minimum tolerable depth to the water table are poorly understood. Work by Hosner (1960), Broadfoot and Williston (1973), Johnson and Bell (1976) and Robertson (1992) list numerous factors that affect growth of a variety of tree species of the deciduous forests of eastern and southeastern United States. However, little quantitative information is available for the common species of the boreal forest of northern Canada, including tamarack (*Larix laricina* (Du Roi) K. Koch), black and white spruce (*Picea mariana* (Mill.) BSP and *Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.) and others. Denyer and Riley (1964), in a published work on tamarack in northern Saskatchewan, concluded that mortality and dieback resulted from high water but presented no quantitative data. Robichaud and Bégin (1997) detail the death and decline of red spruce (*Picea rubens* Sarg.) 3m above a marsh as the result of rising sea level in New Brunswick, but they make no mention of the depth to the water table. Bégin et al., (1993) found that tamarack colonize an emerging shoreline to within a vertical distance of 20-40 cm above the water table, whereas white spruce was much more sensitive and only came to within 120-140 cm of the water table along the emerging coast of eastern Hudson Bay.

The present study was designed to investigate the effect of different water levels on the age, trunk diameter and height of tamarack. Determining the maximum tolerated water table height on the growth of tamarack will allow for a better estimate of the minimum possible elevation that subfossil trees used in geological studies grew above the water table. Consequently, more precise calculations of the rate of change in the elevation of the water table over time may be made. It is recognized that different tree species have different tolerances to prolonged high water levels and some species may live for years with few adverse effects (Broadfoot and Williston, 1973). For the purpose of the present study it is assumed that the water level of the fen has been relatively static over the last few years and that the trees are in equilibrium with their environment although this is not necessarily correct. Additional studies focusing on past water-level fluctuations and tree-ring responses are ongoing.

This study will supply background information necessary for a better estimate of the rate of water level rise in Lake Winnipeg over the last few centuries; a subject of considerable interest in Manitoba as it relates to problems of coastal submergence and shoreline erosion (Nielsen, 1998; Forbes and Frobel, 1996; Tackman et al. 1998). Tamarack has been found to be a particularly useful species for investigating recent water-level changes because of its wide spread occurrence along the shores of Lake Winnipeg and its demonstrated ability to record water-level changes in its tree-ring growth patterns (Nielsen, this volume).

STUDY AREA

A patterned tamarack fen, in east-central Manitoba, located 9 kilometres northwest of the community of Red Sucker Lake, was chosen for the investigation (Fig. 1). Easy access and the occurrence of only a single tree species (tamarack) over most of the area, in a relatively open environment away from competing trees, makes this an ideal study site. A southerly flowing water track, which is an area of concentrated water flow with few or no trees, runs down the long axis of the fen (Fig. 2A). On either side of the water track, small tamarack give way to larger tamarack and then black spruce at the edge of the fen (Figs. 2B, 2C, 2D). The total width of the fen at the site of the investigation is 0.5 km.

METHODS

The relative elevations of the muskeg surface and the water table were measured with a transit at ten metre intervals along the winter road that crosses the fen at right angles from east to west (Fig. 2A). Survey lines were measured to the east and west from a common point in the center of the water track. Photographs recording the tree height and vegetation composition were also taken at ten metre intervals across the fen. In addition, cross-sectional stem discs were collected from representative tamarack and black spruce trees (where present) at approximately ten metre intervals to determine the change in growth characteristics relative to the water table. This might indicate that some essential requirement for growth and survival is nearing the limit of the range of tolerance for these species. The depths to the water table and the highest adventitious root were measured in a small hand-dug hole adjacent to several trees close to the water track and at the 15 tamarack and 4 black spruce trees sampled east of the water track.

In the laboratory, the stem discs were sanded with 120 grit sandpaper. The number of annual rings in each disc was determined under a microscope using 40 X magnification. The diameter of each disc was measured with a ruler to the nearest millimetre.

RESULTS

Topography

The water track, that runs down the long axis of the fen, is approximately 50 m wide and extends from about 30 m east to about 20 m west (Fig. 3). The cross-sectional profile slopes gently to the west, perpendicular to the water track and the long axis of the fen (Figure 2A). The level of the muskeg (fen surface) rises slightly between approximately 60 m west and 60 m east forming a slightly higher and treeless area centered on the water track. The lowest part of the profile is along the western margin where surface water was encountered at 240 m (Figs. 2A and 3). Muskeg gives way to till at the western end of the profile, coincident with the sharp rise in elevation at 290 m west. The rise in the profile at 180 m east is coincident with the change from tamarack fen to black spruce bog.

Hydrology

The surveyed water table generally mimics the topography of the muskeg surface with a broad area of near surface water occurring in the water track between approximately 80 m west and 80 m East. To the east the water table is lowest between 100 and 130 m, whereas in the west, between 100 and 180 m, the level is below 60 cm and was not recorded (Fig. 3). Trees are generally absent in the water track except for a few small (up to 3 m high) gnarled tamaracks (Fig. 2B).

The absence or scarcity of trees in the water track and the presence of small, live but gnarled tamaracks, interspersed with dead and moribund tamaracks (Figs. 2B, 2C) in the area adjacent to the water track, is believed to be the result of stress caused by the higher water level in this area. The drop in the water table away from the water track towards the margins of the fen is manifested by the appearance of taller and straighter trees. The tamarack give way to black spruce on better drained sites (Figs. 2A, 2D).

Through the water track, the depth to the water table, as determined by leveling, is as little as 30 cm (Fig. 3). To the east the depth increases to between 50 and 60 cm and to the west depths range from zero to 90 cm.

Measured depths to the water table, east of the water track, range from 22 to 38 cm for tamarack and 27 to 50 cm for black spruce. From 20 m to 90 m East, the measured depth to the water table is relatively constant between 22 and 30 cm despite the fact that the water table comes closer to the surface toward the middle of the water track. The tamarack have responded to the higher water level by producing adventitious roots above the general level of the surrounding muskeg surface. The adventitious roots are encapsulated in a "muskeg" mound that has formed around the base of the trunk and that stands proud of the surrounding muskeg surface. These "muskeg" mounds are particularly prominent in and adjacent to the water track. As a result there is no appreciable decrease in the measured depths to the water table east of the water track. The measured depth to the water table (Fig. 3) was determined from the highest adventitious roots in the "muskeg" mound and not the general muskeg surface as in the transit survey. For this reason the measured data and the survey data are not directly comparable. Additional discrepancies between the leveling and the measured values may be the result of problems in accurately determining the top of the muskeg surface which may be quite irregular in places. Erratic values in the measured depths may suggest insufficient time was allowed for the water to reach equilibrium at some sites, although this seems unlikely as the measured values are in all instances less than those derived by leveling.

Trunk diameter

Tamarack trunk diameters are uniformly narrow through the water track, ranging from 52 to 63 mm and increase to 135 mm to the west (Fig. 3). To the east the trunk diameters increase to 90 mm in a somewhat erratic manner, and reach values of 140 mm near the eastern end of the transect.

Apical dominance

The height of the trees generally increases away from the water track and is associated with the loss of apical dominance (Fig. 3). Trees near the water track are commonly small and rectangular in shape with flat crowns, multiple stems and complex branching patterns (Fig. 2C). Apical stems, if present, are generally dead. Trees near the margins of the fen are taller and straighter than those near the water track and are typically triangular in shape with a single trunk and a prominent apical leader (Fig. 2D). Branches are well formed and grow upward in a regular fashion. Short, stunted trees showing loss of apical dominance occur in areas where the depth to the water table is less than approximately 60 cm, whereas tall straight trees dominate in areas where the water table is deeper.

Tree ages

The age of the tamaracks along the profile generally increases from west to east. The youngest trees, at the western end of the transect, are only 22 years old, whereas the trees near the eastern end are up to 246 years old. A single anomalous, 242 year old tree, was found 178 m along the western transect, indicating older trees occur to the west of the water track as well. The younger trees in the west may have grown in response to clearing of the winter road highlighting a possible shortcoming of a two dimensional as opposed to a three dimensional survey. Alternatively, the western transect may cut through a stand of younger, higher trees as suggested in Figure 2A.

CONCLUSIONS

Topographic profiling and direct measurement of the elevation of the water table across a patterned fen in east-central Manitoba suggests the growth and development of tamarack may be limited by a shallow water table. Tamarack does not appear to tolerate water levels less than about 22 cm below the ground surface. Trees growing around the water track, where the water table is 22 cm below the ground surface, are shorter, display loss of apical dominance and have smaller trunk diameters than trees growing farther away. In response to higher water levels tamaracks develop adventitious roots that become encapsulated in "muskeg" mounds around the base of their trunks. Only where the water table is greater than 60 cm below the surface are the tamaracks tall, straight, fast growing and show apical dominance. Black spruce does not appear to tolerate water levels less than 40-50 cm, although a single tree was found where the depth to the water table was only 30 cm.

ACKNOWLEDGEMENTS

I would like to thank Gaywood Matile of Manitoba Energy and Mines and Harvey Thorleifson of the Geological Survey of Canada for their insightful and thought provoking discussions, as well as their editorial comments on the manuscript.

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FIGURES

Figure 1. Location of Red Sucker Lake.

Figure 2. (A) The Red Sucker Lake patterned fen viewed from the south. The winter road (WR) where the survey was carried out is the straight line cutting across the fen. The ends of the survey lines are marked with white ticks. The water track (WT) is the light green treeless area in the middle of the fen and the dark green areas are dominated by black spruce. Tamarack fen (T) is the intermediate green colour occurring between the water track and the black spruce (BS). (B) Details of the edge of the water track showing shrubs and small scattered tamaracks. (C) Details of the tamarack east of the water track showing loss of apical dominance, multiple stems and irregular branching pattern. (D) Tall, straight tamarack, showing apical dominance and regular growth form interspersed with black spruce, near the eastern end of the survey line.

Figure 3. East-west profile across the Red Sucker Lake fen showing the land surface morphology, water table height, tree height, trunk diameter and tree age. The measured depths to the water table for tamarack (Tam) and black spruce (BS) along the eastern survey line are also shown.

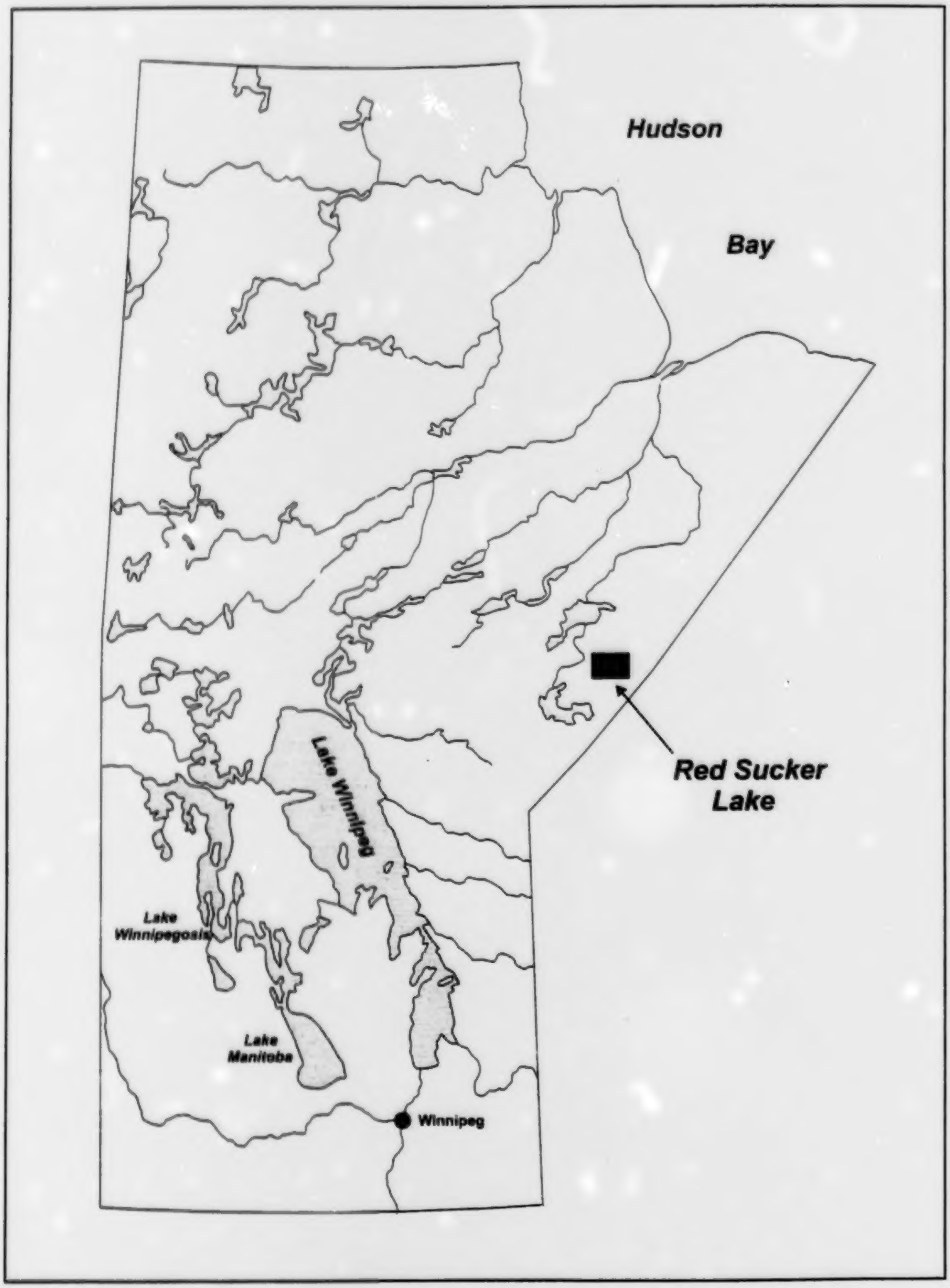
Hudson
Bay
Red Sucker Lake
Lake Winnipeg
Lake Winnipegosis
Lake Manitoba
Winnipeg

Figure 1.

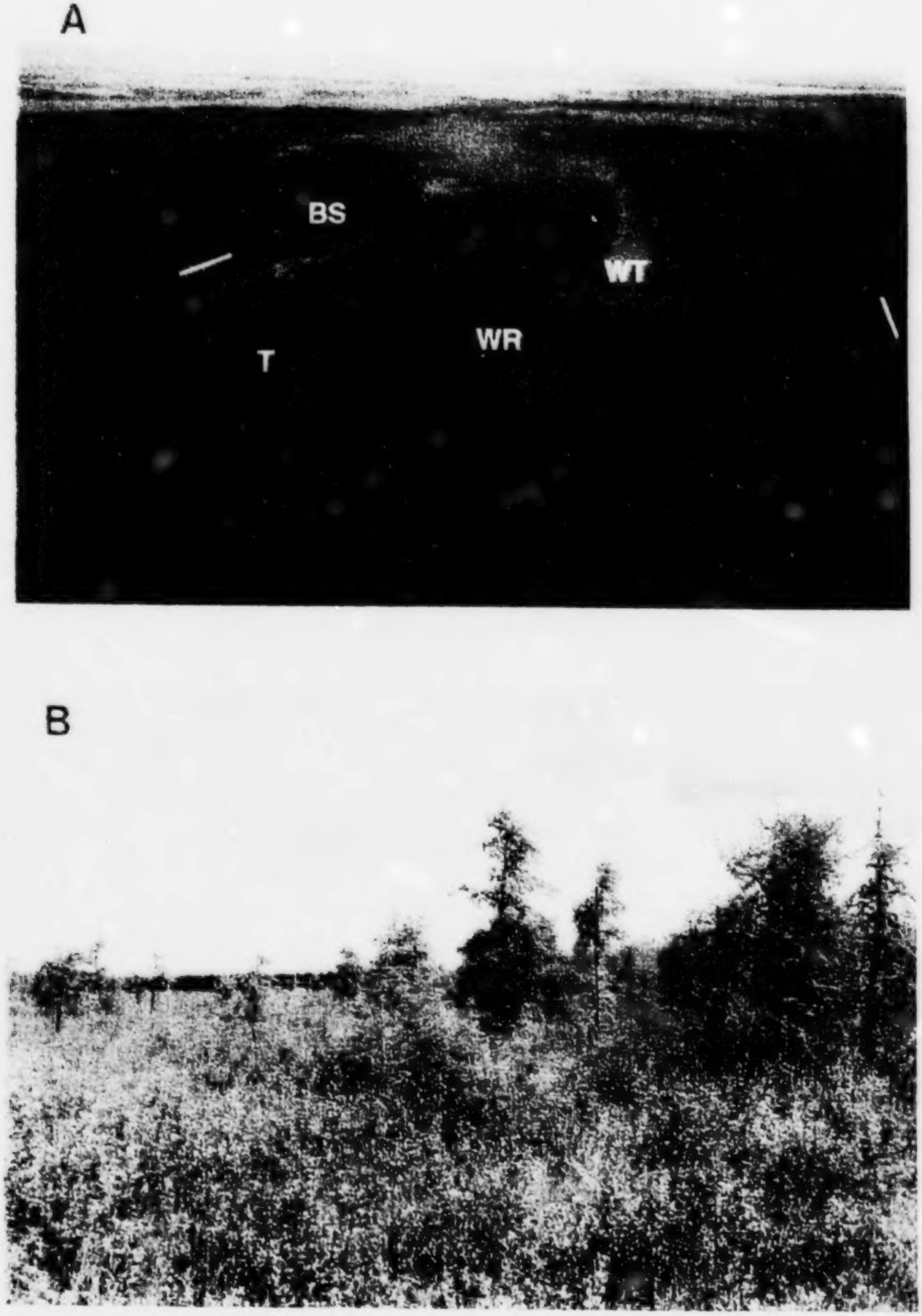

Figure 2.

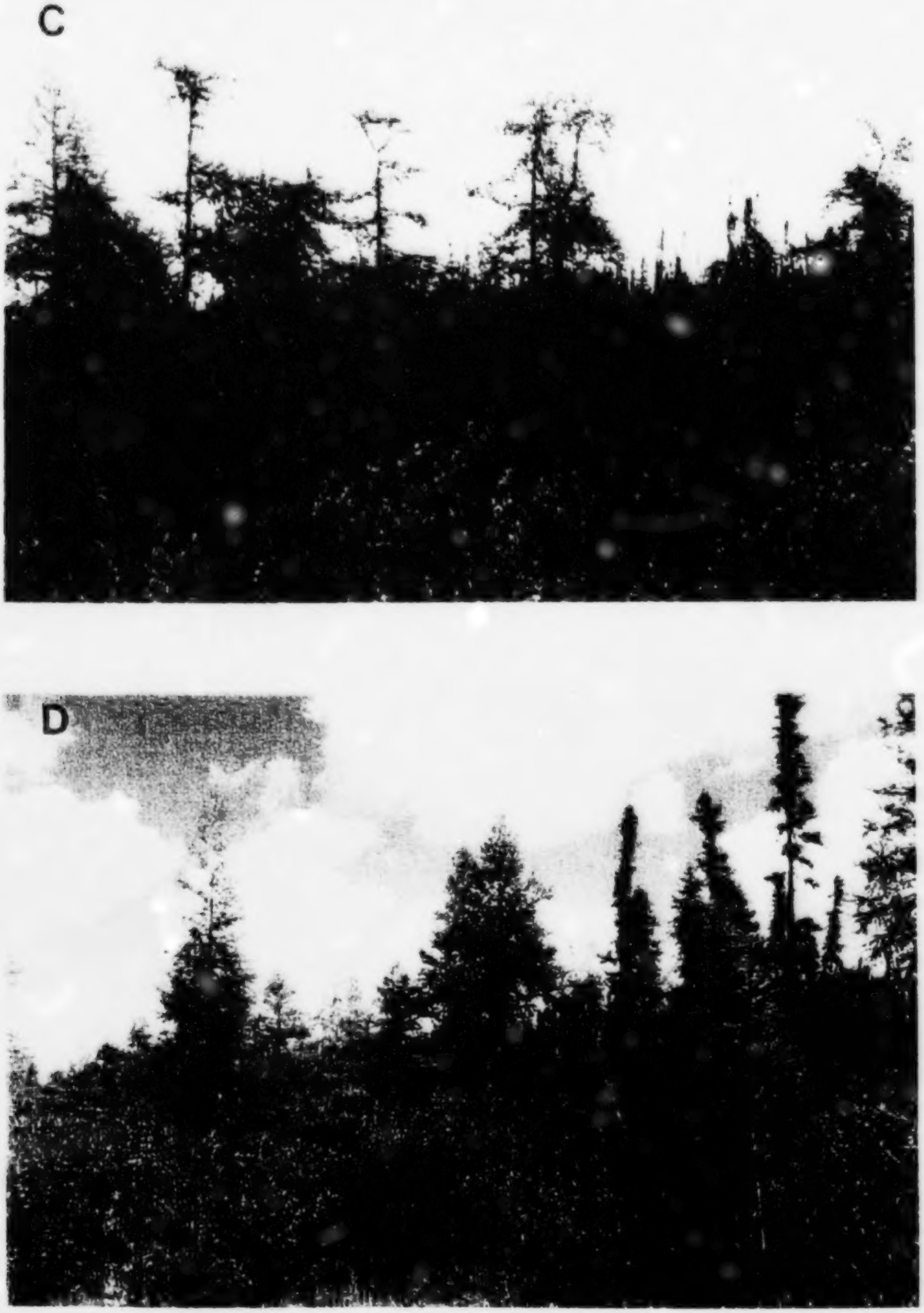

Figure 2. Continued.

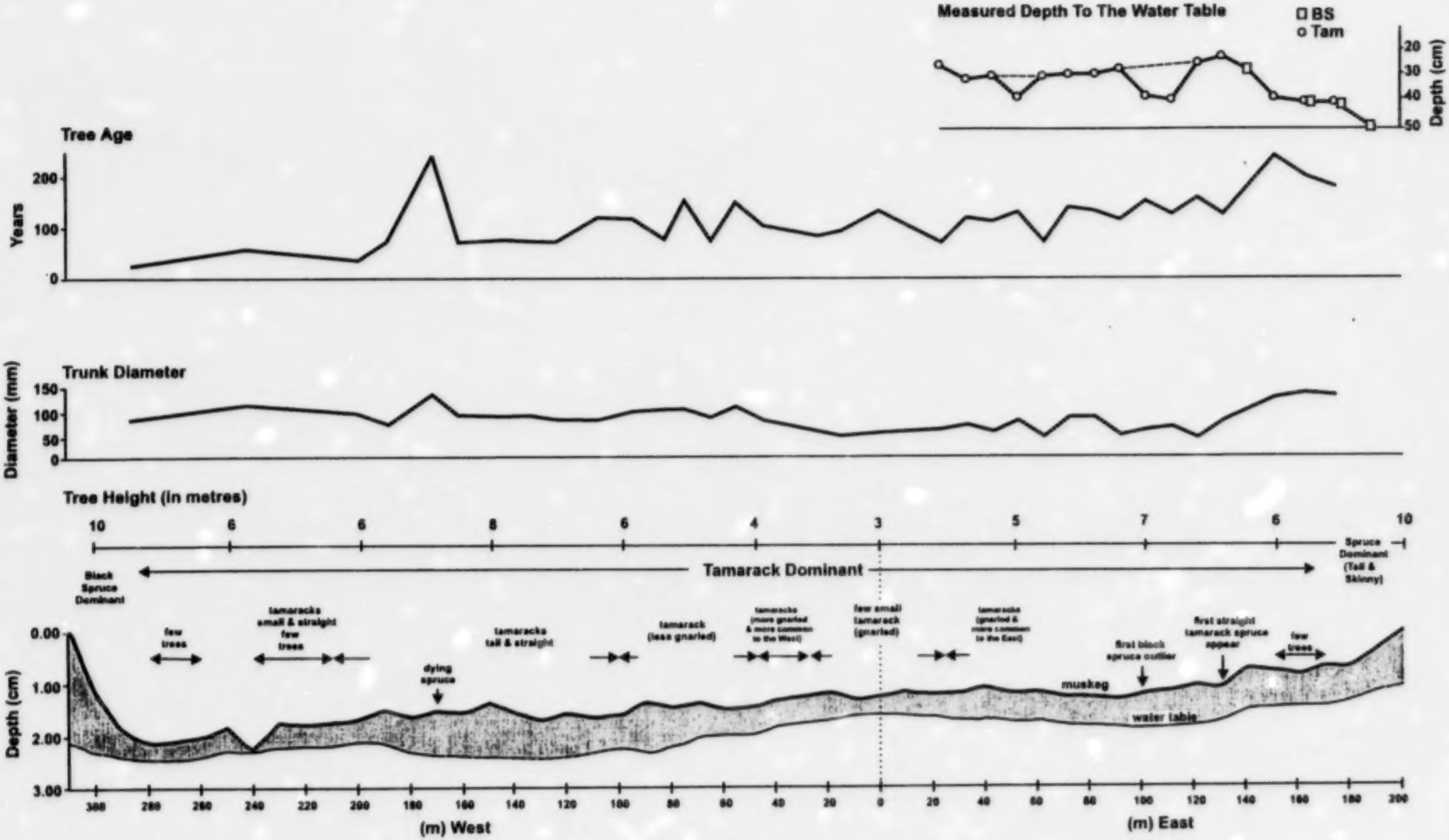
Measured Depth To The Water Table
□ BS
○ Tam
Depth (cm)
20
30
40
50
Tree Age
Years
200
100
0
Trunk Diameter
Diameter (mm)
150
100
50
0
Tree Height (in metres)
10
6
6
8
6
4
3
5
7
6
10
Black Spruce Dominant
Tamarack Dominant
Spruce Dominant (Tall & Skinny)
few trees
tamaracks small & straight few trees
dying spruce
tamaracks tall & straight
tamarack (less gnarled)
tamaracks (more gnarled & more common to the West)
few small tamarack (gnarled)
tamaracks (gnarled & more common to the East)
first black spruce outlier
first straight tamarack spruce appear
few trees
muskeg
water table
Depth (cm)
0.00
1.00
2.00
3.00
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
160
180
200
(m) West
(m) East

Figure 3.

9.7 A model for postglacial expansion of Lake Winnipeg based on postglacial uplift

G.L.D. Matile[1], L.H. Thorleifson[2], and C.F.M. Lewis[3]

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3. Geological Survey of Canada (Atlantic), Dartmouth, Nova Scotia B2Y 4A2

ABSTRACT

A determination of the cause of observed large changes in the extent of Lake Winnipeg during postglacial time, whether due to uplift or due to water supply fluctuations related to climate and/or river diversions, can be made through comparison of observations to predictions based on current knowledge of these mechanisms. Confirmation that uplift has played a role requires comparison of observations to a model that imposes current knowledge of uplift on basin geometry. Alternatively, an inference that climate has been a factor would be based on a deviation of observations from predictions of regional uplift, and concordance with regional paleoclimate records. To facilitate this analysis, a model was constructed by synthesizing observations of uplift from raised shorelines, water level gauges and global rebound models, reconstructing basin geometry prior to sedimentation in Lake Winnipeg from core and seismic observations, considering and discounting outlet downcutting as a factor, inspecting the basin for intermediate sills, tilting reconstructed bathymetry for seven stages, and by reconstructing the single or multiple lakes that would have occurred at the time. The analysis indicates that, assuming the maintenance of positive hydrological budgets, the north basin has more than doubled in extent since the retreat of Lake Agassiz, and the south basin would have increased nearly ten-fold.

INTRODUCTION

A key issue addressed by the Lake Winnipeg Project (Todd et al., 1998a) has been the degree of and cause of postglacial evolution in the extent of the lake, in order to better understand topics such as present-day shoreline erosion. The degree of change in lateral extent has been indicated by stratigraphy and geochronology (Lewis et al., this volume). The cause or causes of these changes can be inferred, in order to better understand and predict their future course, by comparison of observations to model predictions based on specific assumptions. Conformity of observations to the predictions of the effects of uplift would indicate dominance of uplift. In contrast, deviation of observations from the predicted course of evolution due to uplift, in concordance with regional paleoclimate records, with lakes smaller than those predicted here, would instead indicate a role for climate. This would indicate episodes of hydrological deficit, due for example to low precipitation and/or high evaporation (Lewis et al., this volume). To facilitate this analysis, a model for postglacial expansion of an overflowing Lake Winnipeg, based only on the effects of differential postglacial uplift, was required and is presented here.

BASIN EVOLUTION

The likely drivers of lake evolution in the case of Lake Winnipeg are uplift and water supply fluctuations related to climate and/or river diversions. It has been established that significant postglacial uplift has occurred in the region (Johnston, 1946; McMartin, 1996; Nielsen et al., 1987; Tackman et al., 1998; Tackman et al., 1999). Climate also has undergone significant change during the Holocene (e.g. Ritchie, 1976; Anderson and Vance, this volume). Outlet down-cutting is discounted as a factor capable of imposing large changes in the extent of Lake Winnipeg; the Warren Landing sill is shallow and formed in readily eroded sediments, so it is likely to have been quickly eroded to its current configuration in immediate post-Lake Agassiz time. Changes in water supply due to Mid-Holocene diversion of the Saskatchewan River to Lake Winnipeg (McMartin, 1996) and switches of the Assiniboine River between Red River and Lake Manitoba (Rannie et al., 1989) are evaluated elsewhere (Lewis et al., this volume). For the purpose of this exercise, water budget of Lake Winnipeg was assumed to be positive throughout postglacial time.

RECONSTRUCTION OF PRE-LAKE WINNIPEG TOPOGRAPHY

A set of selected bathymetric points from Canadian Hydrographic Service Charts 6240 and 6241 were digitized and the depths were converted to feet by multiplying fathom values by 6. Mean lake level was set at 713.4', the mean of all Environment Canada lake level values for the Berens River gauge. On Chart 6240 for the south basin, sites south of 51°30' are referenced to a datum of 717.3' (218.6 m), said to be mean lake level in 1901. On the same chart, sites north of 51°30', in the Narrows, are referenced to a datum of 711.5' (216.9 m). On Chart 6241 for the north basin, sites are referenced to a datum said to be mean lake level in 1902 and 1903, but a value is not given. A line of soundings about 3 km northwest of Berens Island has several points reported to be 9 fathoms on the north basin chart, but these sites are reported as 8 fathoms on the south basin chart. The datum for the northern portion of the south basin chart is 711.5', and the north basin chart is reporting an extra fathom depth, so the north basin chart datum is assumed to be one fathom or six feet higher than that for the northern part of the south basin (Narrows), 711.5', so the north basin chart datum is considered 717.5'. For sites north of 52° (North Basin), the depths in feet therefore were corrected to a datum of 713.4' by subtracting 4.1' (717.5-713.4). For sites between 52°15' and 51°30' (The Narrows), the depths in feet were corrected to a datum of 713.4' by adding 1.9' (713.4-711.5). For sites south of 51°30' (South Basin), the depths in feet were corrected to a datum of 713.4' by subtracting 3.9' (717.3-713.4).

In order to reconstruct basin geometry prior to sedimentation in Lake Winnipeg, ratios of water depth to thickness of the Lake Winnipeg sediments that overly Lake Agassiz sediments were examined. For example, 4.3 m of Lake Winnipeg sediments in 9.8 m of water at site 122 produces a ratio of 0.44, and 6.86 m of Lake Winnipeg sediments in 15.9 m of water at site 103 gives a value of 0.43 (Lewis et al., this volume; Table 1). The available observations give a range of values with a mean of about 0.25. A ratio was not determined for some sites, where the Lake Winnipeg sediment sequence was not fully penetrated, or where the contact between Lake Winnipeg and Lake Agassiz sediments was uncertain. All corrected bathymetric data therefore were multiplied by 1.25, in order to approximate the pre-Lake Winnipeg topography. An exception was the elevation of sills, which are likely to have been too shallow for significant sedimentation and whose elevation are key factors in the model. Although some erosion of the pre-Lake Winnipeg surface would have occurred during expansion of Lake Winnipeg, no allowance was made for this factor, although the landscape may have been lowered, perhaps by 1 to 3 m in many areas, based on the morphology of present-day shore bluffs (Forbes and Frobel, 1996).

The estimated depths below lake level to the base of Lake Winnipeg sediments were converted to elevations by subtracting from 713.4', and the values were converted to metres. The present-day shoreline was used as a contour line, set to 713.4', and land topography was added using points digitized from NTS 1:250,000 contour lines. The data were then converted to a regular grid of elevation points using a triangular irregular network-based methods, using MapInfo© and Vertical Mapper© geographic information system software.

ESTIMATION OF UPLIFT

Independent estimates of the amount of uplift that has occurred in the Lake Winnipeg region in postglacial time are available from Lake Agassiz shorelines (Johnston, 1946; McMartin, 1996), raised shorelines of Lakes Winnipegosis and Dauphin (Nielsen et al., 1987; Tackman et al., 1998), lake gauge trends (Tackman et al., 1999), and geophysical ice loading models calibrated to the evidence of global relative sea level (Lambert et al., 1998). Late Lake Agassiz shorelines in the Lake Winnipeg region are uplifted to a gradient of about 0.3 m/km toward about N30°E (Johnston, 1946; McMartin, 1996). Mid-Holocene raised shorelines of Lakes Winnipegosis and Dauphin are uplifted on the order of 0.1 m/km (Nielsen et al., 1987; Tackman et al., 1998). Inundated in situ tree stumps beneath southern Lake Winnipeg (Nielsen, 1998) and lake gauge trends (Tackman et al., 1999) indicate that uplift continues at present. These observations are compatible with the trends implied by geophysical models (Lambert et al., 1998). From these observations, estimates for degree of uplift since several points in postglacial time were made (Table 2), ranging from 0.3 m/km at 7.9 C14 ka BP, evolving to horizontal at present. The age of the tilted phases in Table 2 were determined by an exponential model of uplift versus time for the Lake Winnipeg basin (Lewis et al., this volume, Table 9).

RECONSTRUCTION OF LAKES

Lakes were defined as the highest closed contour in the basin (Figure 1), except for contours open at areas of recent erosion in the Narrows (Todd et al., 1998b). No allowance was made for water depth at outlets. This may be reasonable if it is assumed that some sort of channel would have been eroded relative to the bathymetric trends used to build the model.

DETERMINATION OF AREAS

Areas for a north basin lake, a mid-basin lake, and a south basin lake, and the combined lake were obtained (Table 3). For the most recent reconstruction, the mid-basin lake was combined with the north basin, and the three lakes combined to form the modern lake, for which an area is given (Table 3).

DISCUSSION

The model shows that, due to the low gradients of the region, differential uplift would have had a dramatic effect on lake expansion during times of positive hydrological budget. The analysis indicates that the north basin has more than doubled in extent since the retreat of Lake Agassiz, and the south basin has increased nearly ten-fold. The earliest phase reconstructed here, estimated to have an age of 7.9 ka, may not have actually existed due to this age preceding the drainage of Lake Agassiz from the area (Thorleifson, 1996). The model results have been imported by Lewis et al. (this volume) as measures of lake areas in the sub-basins of Lake Winnipeg under the assumption of open, overflowing lake status for comparison with climate-supportable lake areas.

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Table 1. Relationship of Lake Winnipeg sediment sequence thickness to water depth (Lewis et al., this volume)

Site	Water depth (m)	Sediment thickness (m)	Ratio
103	15.9	6.86	0.43
104a	16.1	not penetrated	
105	15.9	0.645	0.04
106	17.1	1.82	0.11
107a	17.1	1.94	0.11
110a	11.3	2.09	0.18
113a	9.8	not penetrated	
115	10.7	not penetrated	
119	9.8	1.71	0.17
120	10.1	1.96	0.19
121	10.4	4.75	0.46
122	9.8	4.265	0.44
201	12.95	4.39	0.34
202	13.63	uncertain	
203	16.46	uncertain	
204	15.85	uncertain	
205	15.85	1.07	0.07
206	15.85	0.69	0.04
207	17.07	1.24	0.07
208	15.85	1.16	0.07
209	16.46	1.04	0.06
212	10.97	not penetrated	
213	11.89	0.15	0.01
214	11.28	3.75	0.33
215	11.58	3.61	0.31
216	11.89	3.42	0.29
217	11.13	uncertain	
218	10.36	not penetrated	
219	10.52	not penetrated	
220	10.52	not penetrated	
221	10.36	5.22	0.50
222	10.36	7.35	0.71
223	9.75	6.775	0.69
224	8.53	not penetrated	

Table 2. Estimated values for present gradient toward N30°E (m/km) of surfaces horizontal at times given in radiocarbon years (ka BP) and calendar years before present (cal yrs BP)

Ka BP	cal yrs BP	m/km
7.90	8840	0.300
7.45	8260	0.250
6.65	7560	0.200
5.87	6680	0.150
4.75	5510	0.100
3.50	3750	0.050
2.35	2350	0.025
0.00	0	0

Table 3. Reconstructed basin areas (km2)

Tilt (m/km)	North	Mid	South	Total Area
0.300	4920	370	390	5680
0.250	6220	790	500	7510
0.200	8280	1050	610	9940
0.150	11450	1210	860	13520
0.100	13070	1440	1280	15790
0.050	14250	1540	1600	17390
0.025	15200		3890	19090
Modern				23580

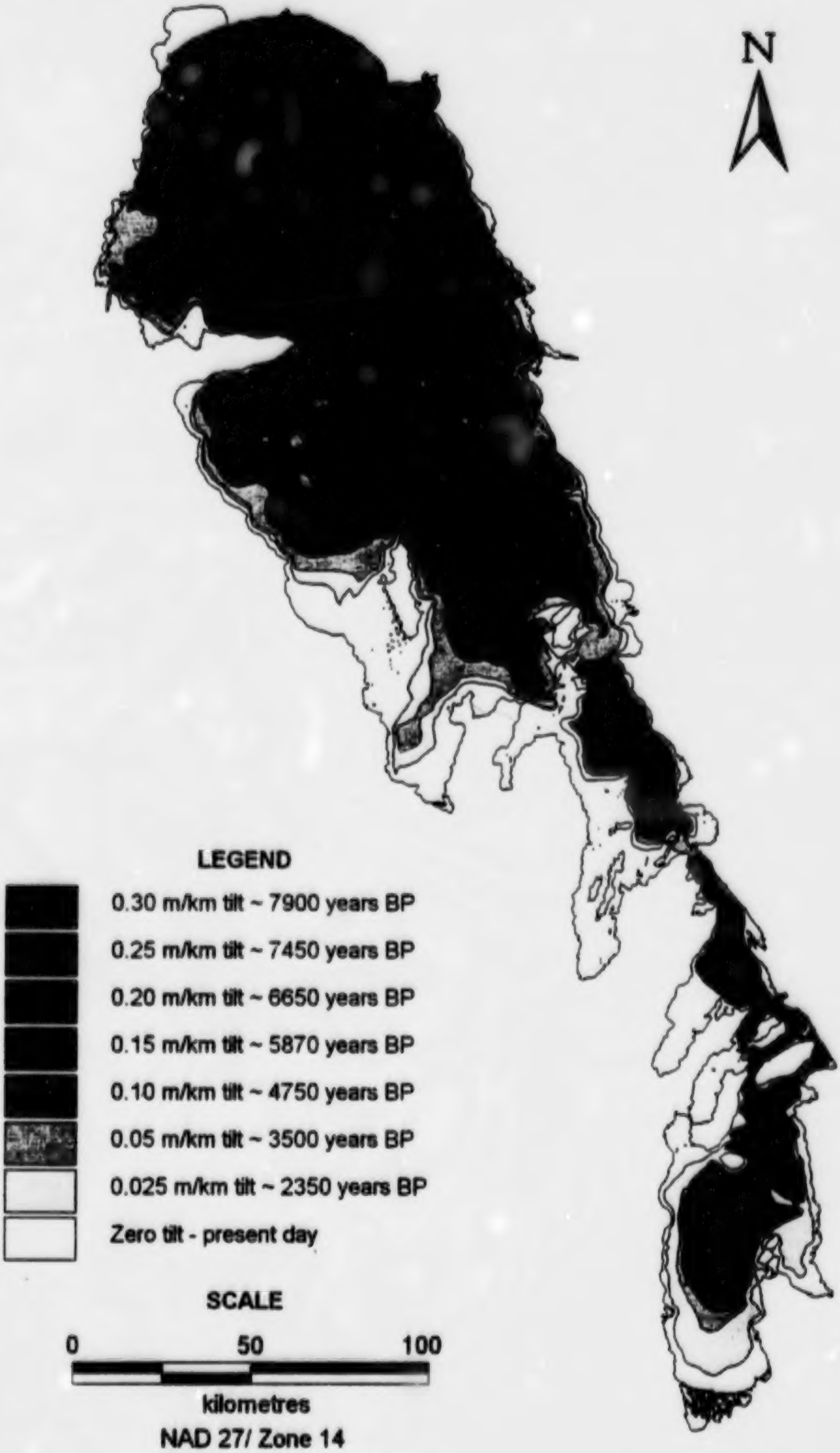

N
LEGEND
0.30 m/km tilt ~ 7900 years BP
0.25 m/km tilt ~ 7450 years BP
0.20 m/km tilt ~ 6650 years BP
0.15 m/km tilt ~ 5870 years BP
0.10 m/km tilt ~ 4750 years BP
0.05 m/km tilt ~ 3500 years BP
0.025 m/km tilt ~ 2350 years BP
Zero tilt - present day
SCALE
0
50
100
kilometres
NAD 27/ Zone 14

Figure 1. Extent of reconstructed lakes, ages indicated in radiocarbon years before present.

Appendix 10.1

Lake Winnipeg Project track plots and sample locations

B.J. Todd[1], C.F.M. Lewis[1], D.L. Forbes[1], A.G. Sherin[1], K.W.G. LeBlanc[1], L.H. Thorleifson[2] and E. Nielsen[3]

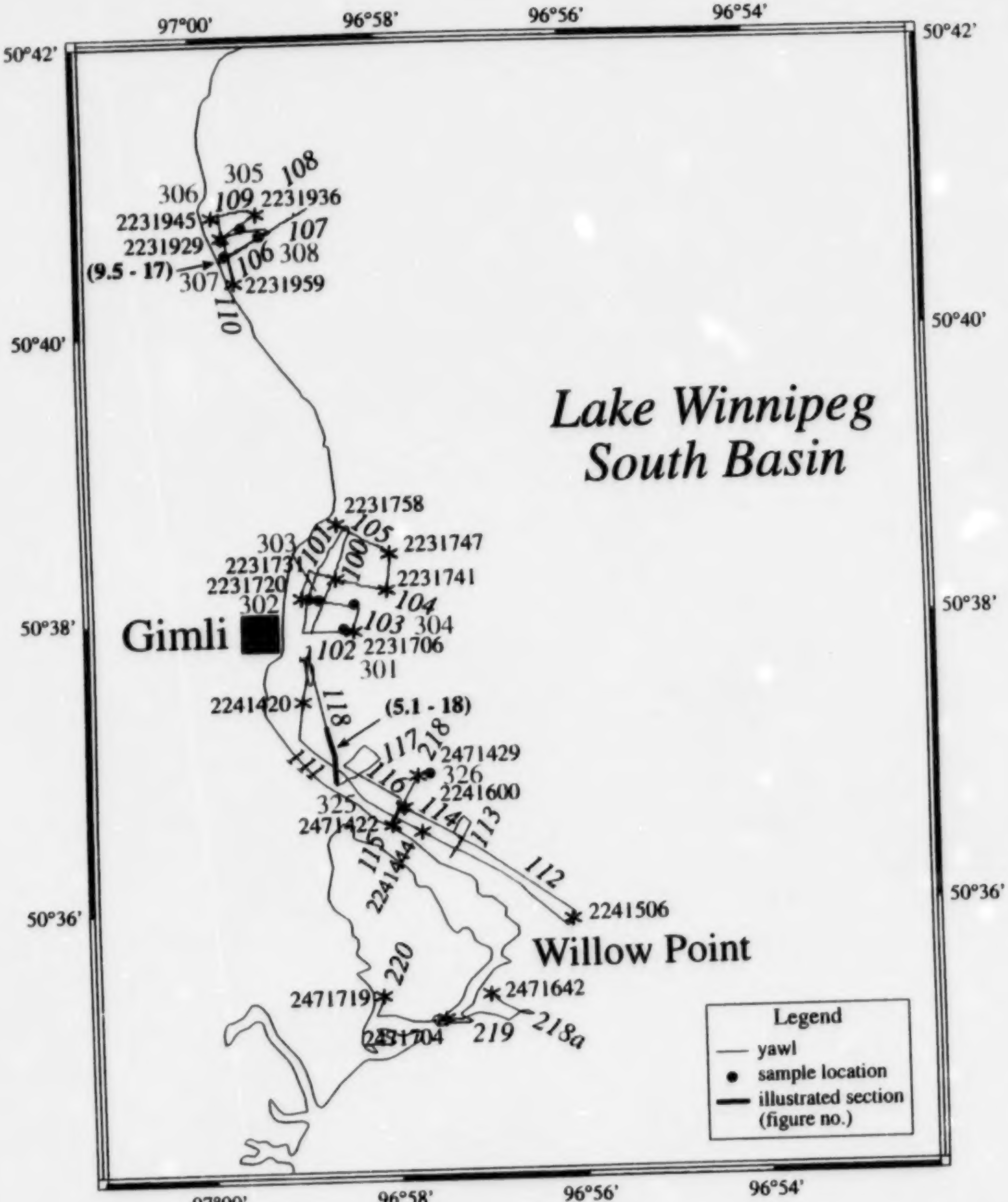
1. Geological Survey of Canada (Atlantic)
2. Geological Survey of Canada, Ottawa
3. Manitoba Energy and Mines

Three large rolled map sheets and sixteen page-sized maps of yawl survey lines accompany this Open File Report on CD-ROM. Map Sheet 1 shows Lake Winnipeg and Lake Manitoba. Survey lines and sample sites are labeled. Boxes outlined by dashed lines are keyed to yawl maps 1 to 16, in order of ascending survey day.

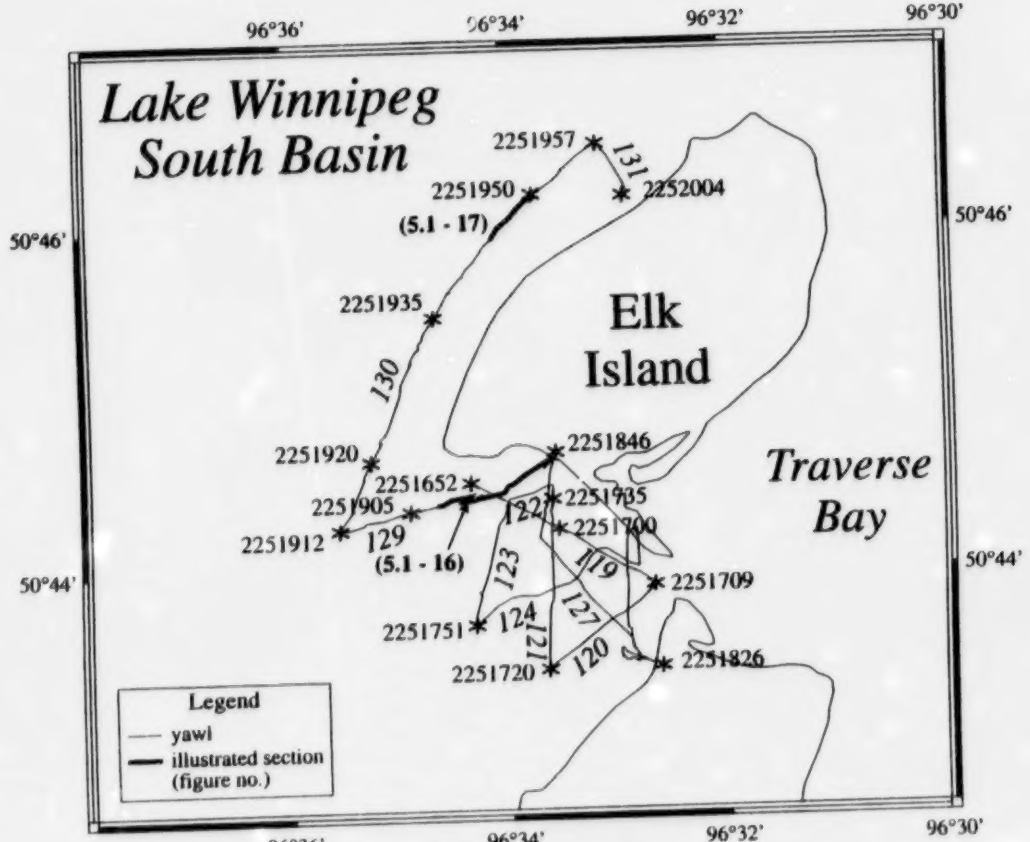
Map Sheet 2 of the South Basin of Lake Winnipeg and Lake Manitoba shows the survey day and time along 1994 and 1996 lines. Also, sample sites are labeled.

Map Sheet 3 of the North Basin of Lake Winnipeg shows the survey day and time along 1994 and 1996 lines. Also, sample sites are labeled.

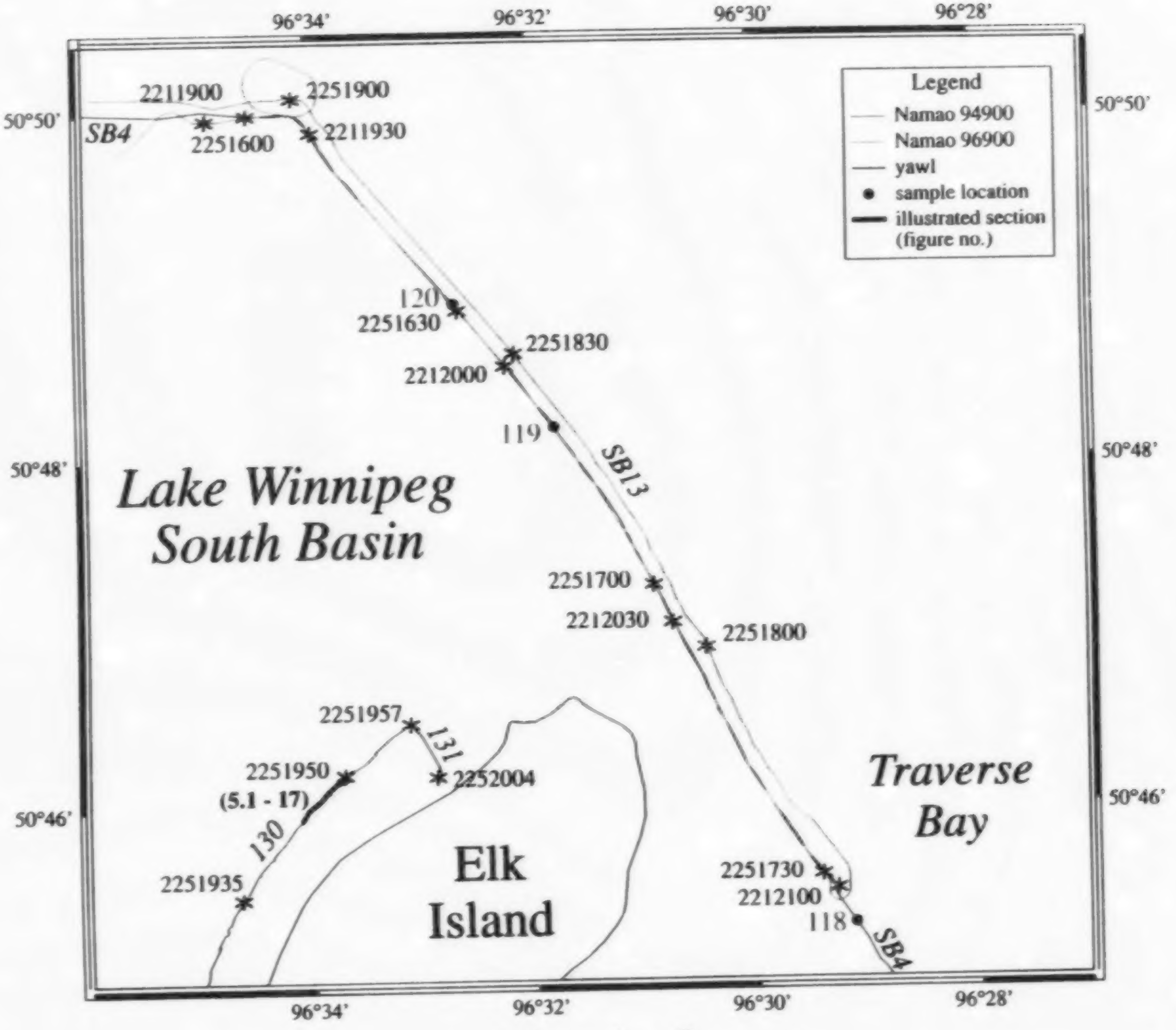
On the sixteen page-sized maps, which also appear in the appendix,1996 yawl lines are illustrated in green, *Namao* 94-900 in blue, and *Namao* 96-900 in red.


97°00'
96°58'
96°56'
96°54'
50°42'
50°40'
50°38'
50°36'
Lake Winnipeg
South Basin
Gimli
Willow Point
305
108
306
109
2231936
2231945
107
2231929
106
308
(9.5 - 17)
307
2231959
110
2231758
105
303
2231747
101
100
2231731
2231720
2231741
302
104
103
304
102
2231706
301
2241420
118
(5.1 - 18)
117
218
2471429
111
116
326
2241600
325
114
113
2471422
115
2241444
112
2241506
220
2471719
2471642
2471704
219
218a
Legend
yawl
sample location
illustrated section (figure no.)

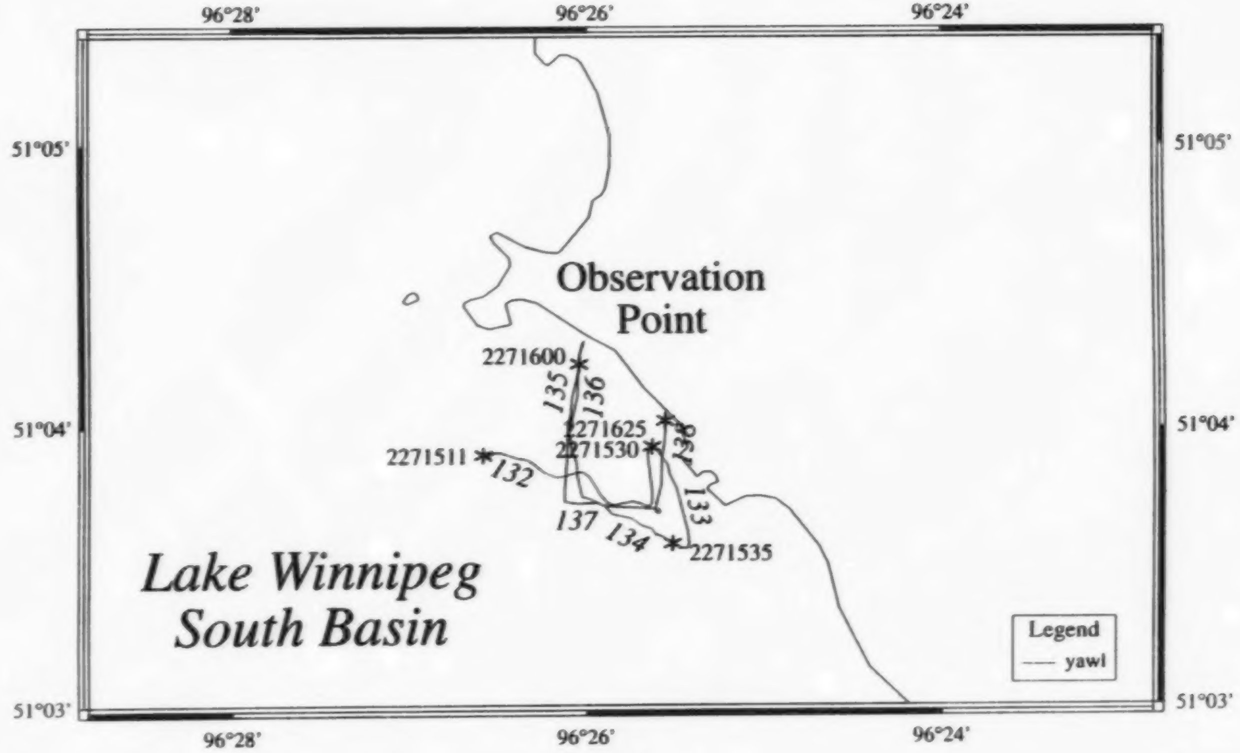
Map 1 - 1


96°36'
96°34'
96°32'
96°30'
50°46'
50°44'
Lake Winnipeg
South Basin
Elk
Island
Traverse
Bay
2251957
131
2252004
2251950
(5.1 - 17)
2251935
130
2251920
2251846
2251652
2251935
2251905
2251700
2251912
129
122
(5.1 - 16)
123
119
2251709
2251751
124
127
121
120
2251826
2251720
Legend
yawl
illustrated section
(figure no.)

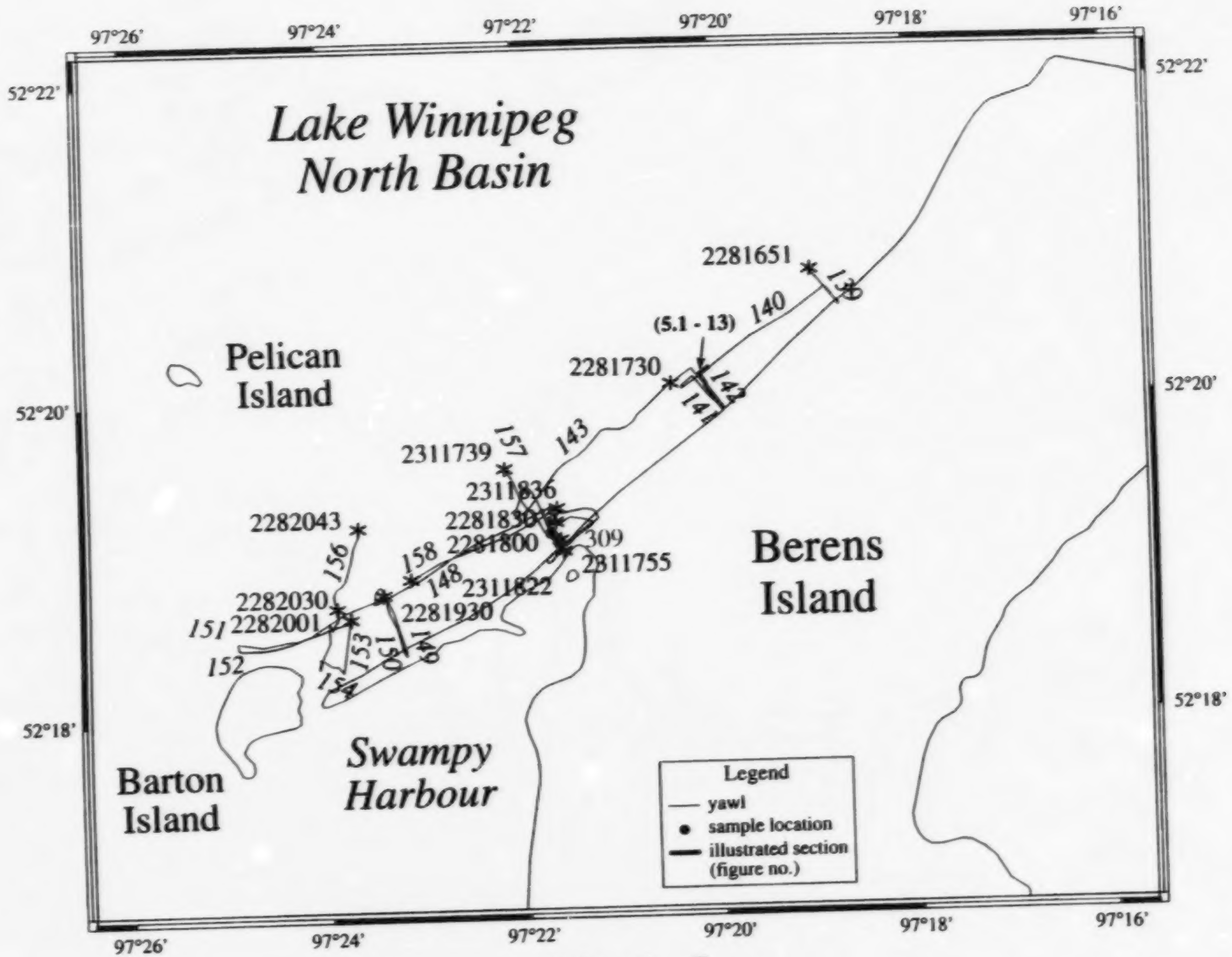
Map 1 - 2


96°34'
96°32'
96°30'
96°28'
50°50'
50°48'
50°46'
Legend
Namao 94900
Namao 96900
yawl
● sample location
illustrated section (figure no.)
SB4
2211900
2251900
2251600
2211930
120
2251630
2251830
2212000
119
SB13
Lake Winnipeg South Basin
2251700
2212030
2251800
2251957
131
2251950
2252004
(5.1 - 17)
130
2251935
Elk Island
Traverse Bay
2251730
2212100
118
SB4

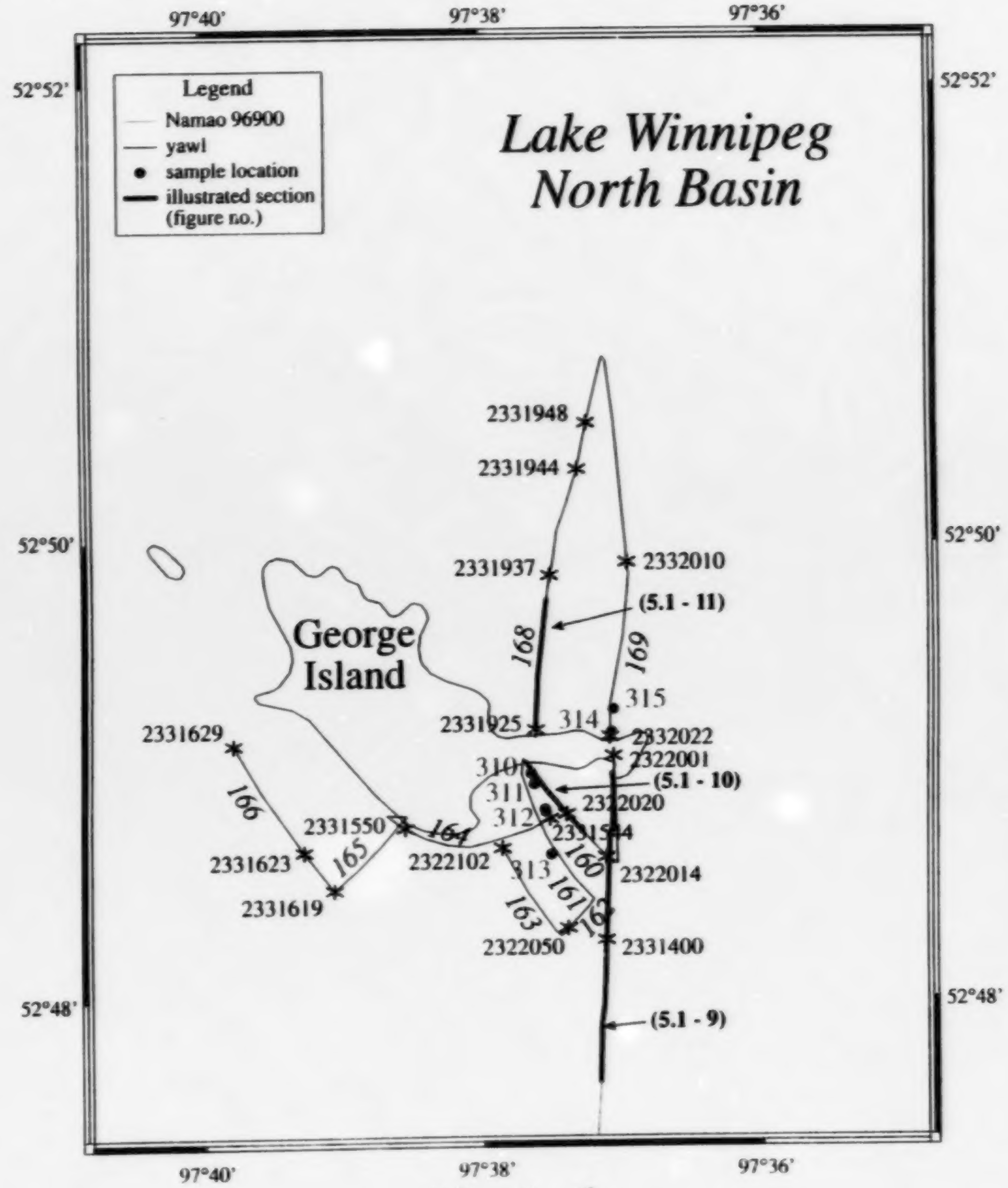
Map 1 - 3

96°28'
96°26'
96°24'
51°05'
51°04'
51°03'
Observation Point
Lake Winnipeg South Basin
2271600
2271625
2271530
2271511
2271535
132
133
134
135
136
137
138
Legend
yawl

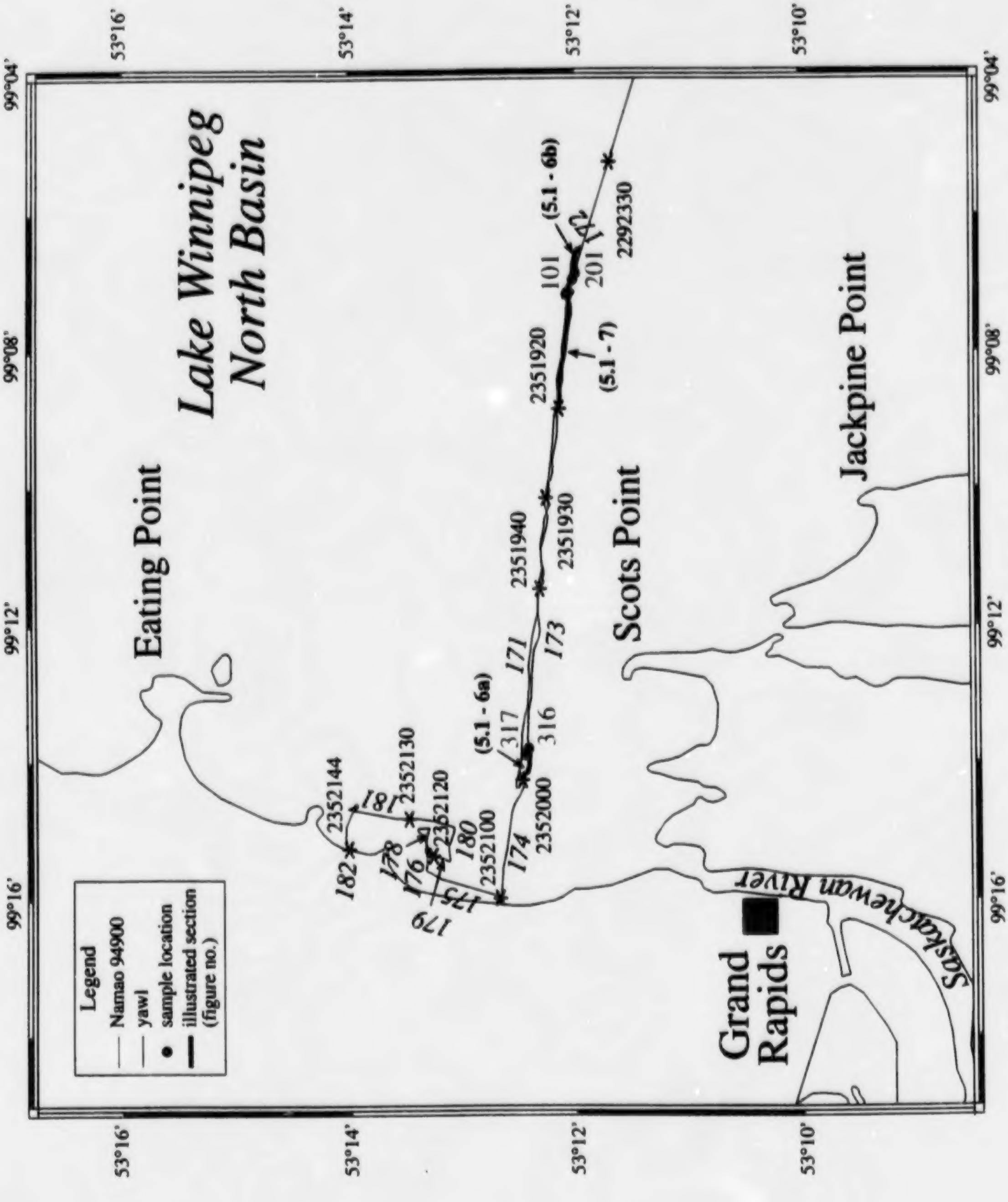
Map 1 - 4


97°26'
97°24'
97°22'
97°20'
97°18'
97°16'
52°22'
52°20'
52°18'
Lake Winnipeg
North Basin
Pelican
Island
Berens
Island
Barton
Island
Swampy
Harbour
2281651
139
140
(5.1 - 13)
2281730
142
141
143
2311739
157
2311836
2281830
2281800
309
2311755
2311822
2282043
156
158
148
2282030
2282001
2281930
151
152
153
150
149
154
Legend
yawl
sample location
illustrated section
(figure no.)

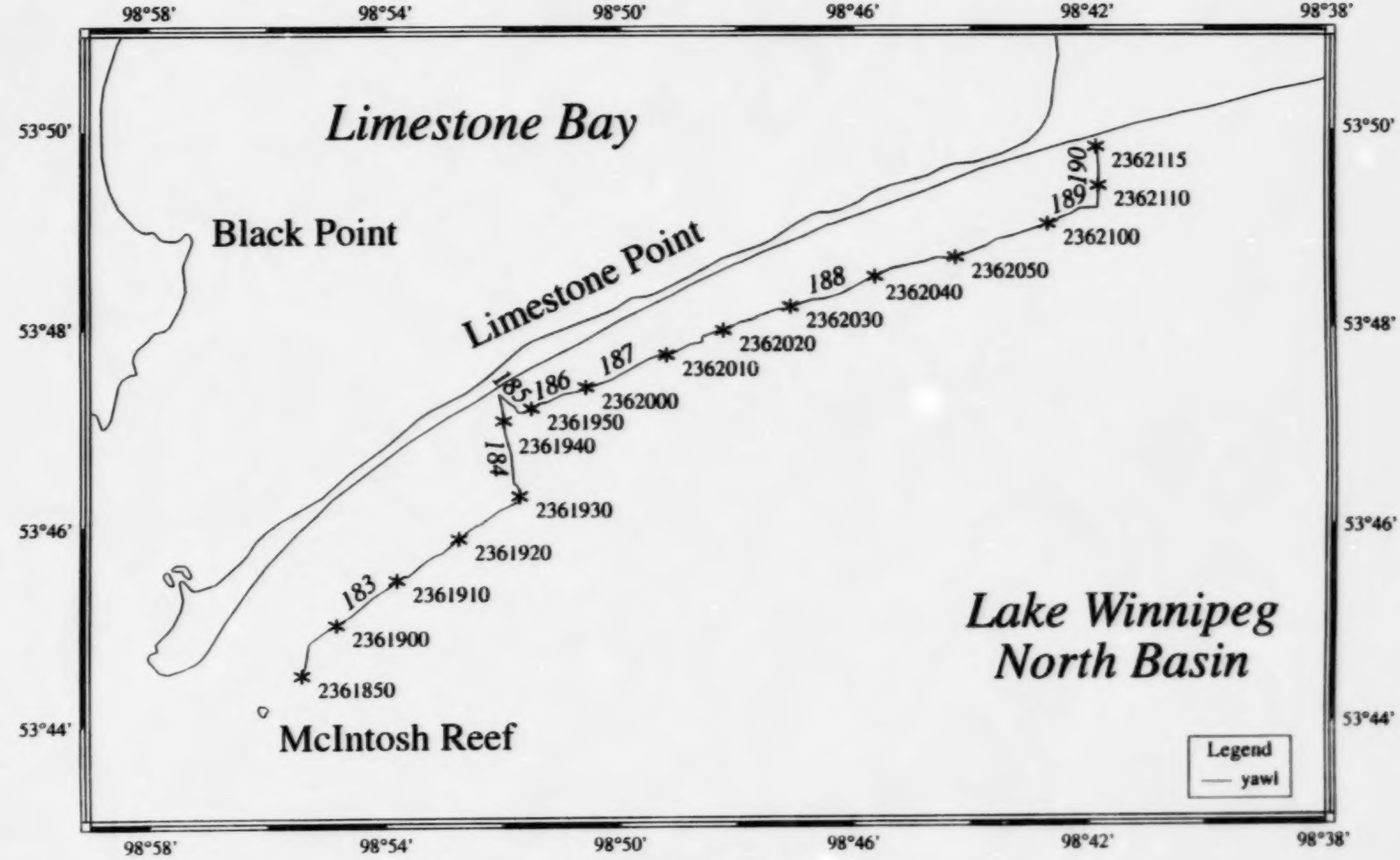
Map 1 - 5

97°40'
97°38'
97°36'
52°52'
52°50'
52°48'
Legend
Namao 96900
yawl
● sample location
illustrated section (figure no.)
Lake Winnipeg
North Basin
George Island
2331948
2331944
2331937
2332010
(5.1 - 11)
168
169
315
314
2331925
2332022
2322001
(5.1 - 10)
310
311
312
2322020
2331544
2322014
160
161
162
313
163
2322050
2331400
(5.1 - 9)
2331629
166
2331550
164
2322102
2331623
165
2331619

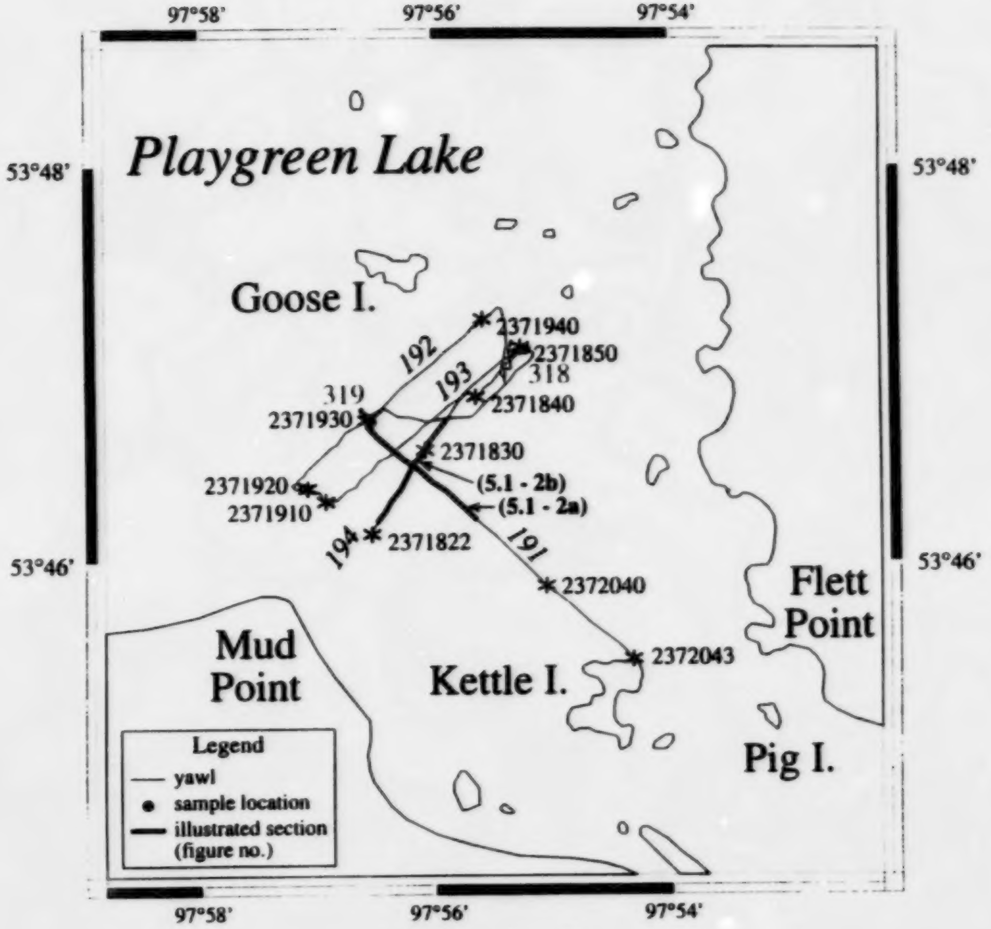
Map 1 - 6


Lake Winnipeg
North Basin
Eating Point
Scots Point
Jackpine Point
Grand Rapids
Saskatchewan River
Legend
Namao 94900
yawl
sample location
illustrated section (figure no.)
99°16'
99°12'
99°08'
99°04'
53°16'
53°14'
53°12'
53°10'
2352144
2352130
2352120
2352100
2352000
2351940
2351930
2351920
2292330
182
181
178
176
175
179
180
174
317
316
171
173
101
201
(5.1 - 6a)
(5.1 - 6b)
(5.1 - 7)

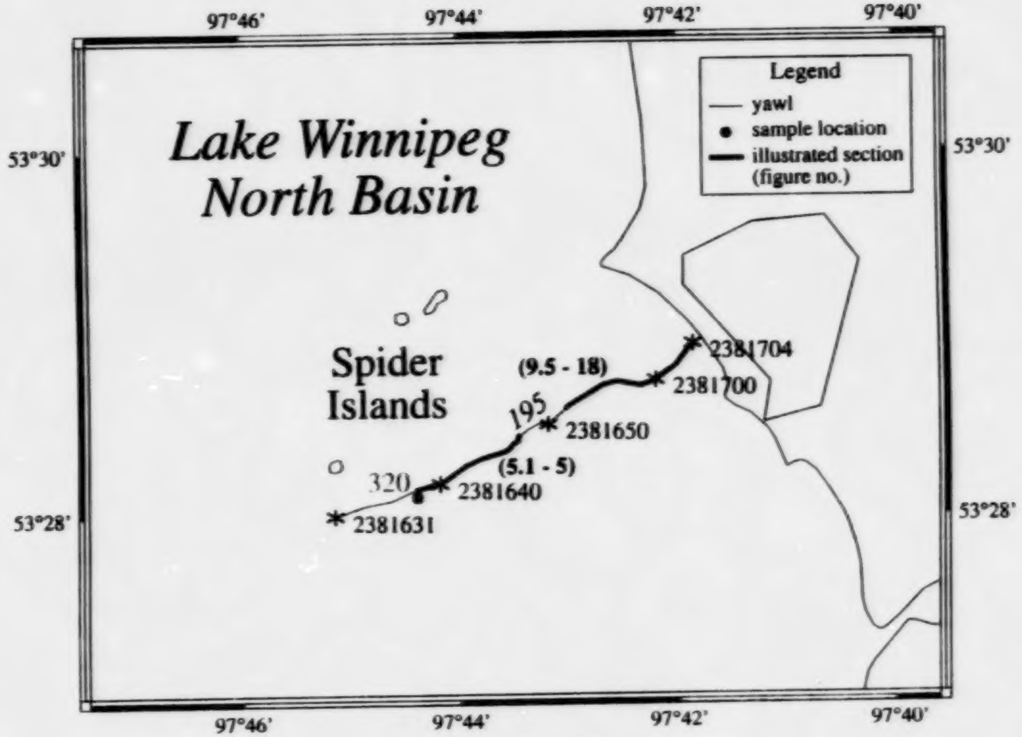
Map 1 - 7


98°58'
98°54'
98°50'
98°46'
98°42'
98°38'
53°50'
53°48'
53°46'
53°44'
Limestone Bay
Black Point
Limestone Point
Lake Winnipeg
North Basin
McIntosh Reef
2362115
2362110
2362100
2362050
2362040
2362030
2362020
2362010
2362000
2361950
2361940
2361930
2361920
2361910
2361900
2361850
190
189
188
187
186
185
184
183
Legend
yawl

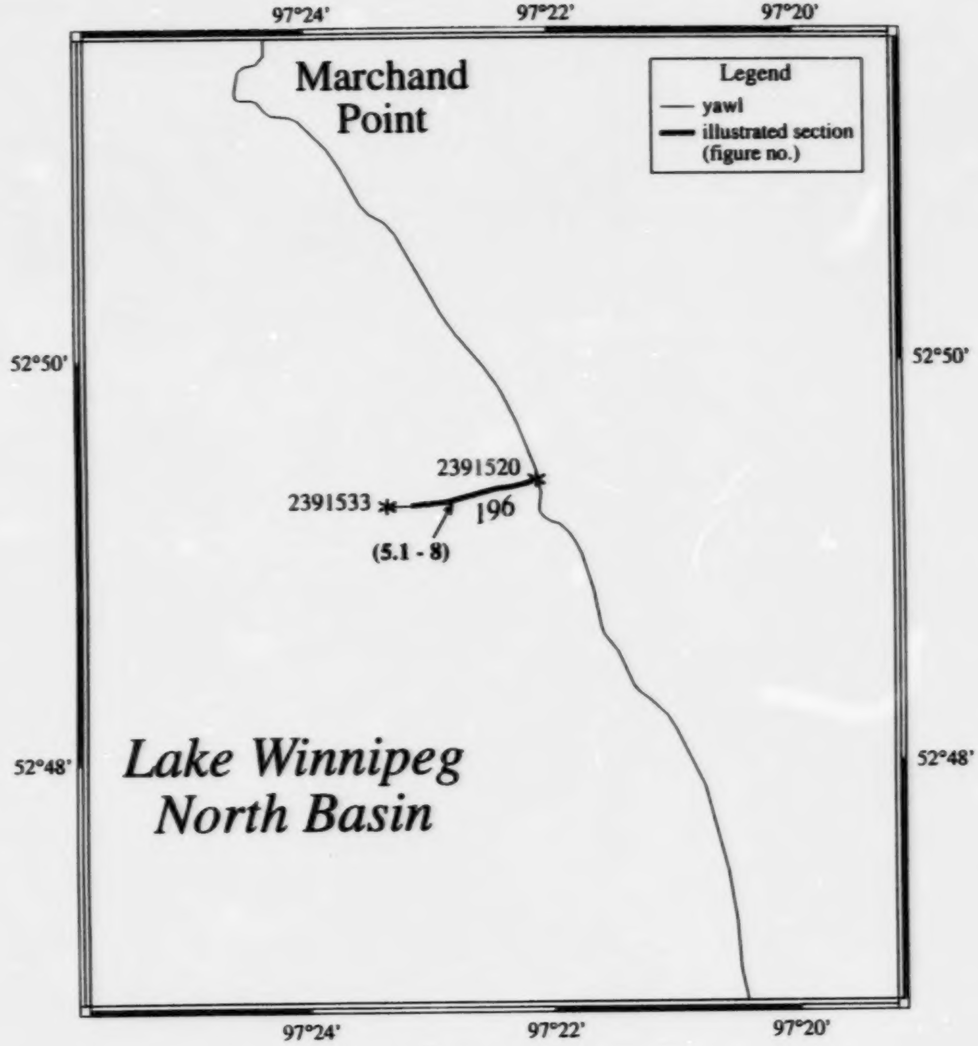
Map 1 - 8


97°58'
97°56'
97°54'
53°48'
53°46'
Playgreen Lake
Goose I.
2371940
2371850
318
192
193
319
2371930
2371840
2371830
2371920
2371910
(5.1 - 2b)
(5.1 - 2a)
194
2371822
191
2372040
Flett Point
Mud Point
Kettle I.
2372043
Pig I.
Legend
yawl
sample location
illustrated section (figure no.)

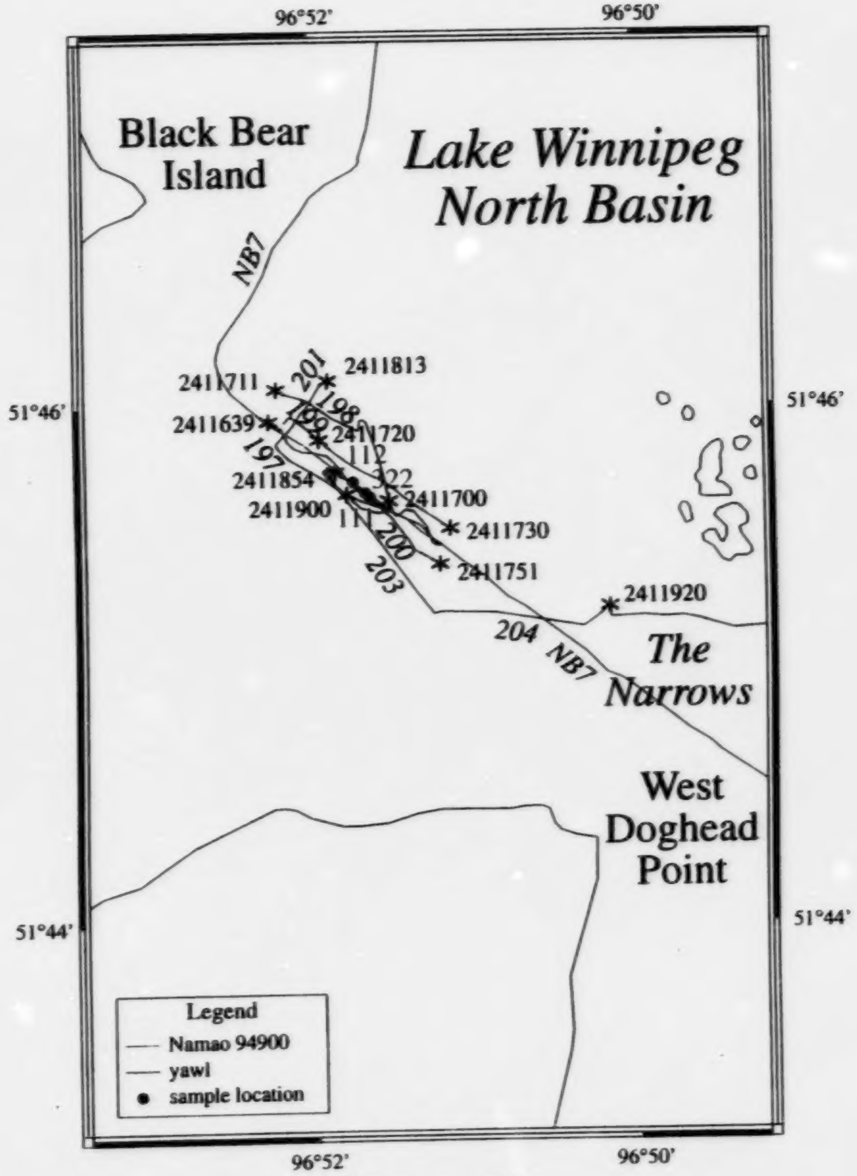
Map 1 - 9


97°46'
97°44'
97°42'
97°40'
53°30'
53°28'
Lake Winnipeg
North Basin
Legend
yawl
sample location
illustrated section
(figure no.)
Spider
Islands
(9.5 - 18)
2381704
2381700
195
2381650
(5.1 - 5)
320
2381640
2381631

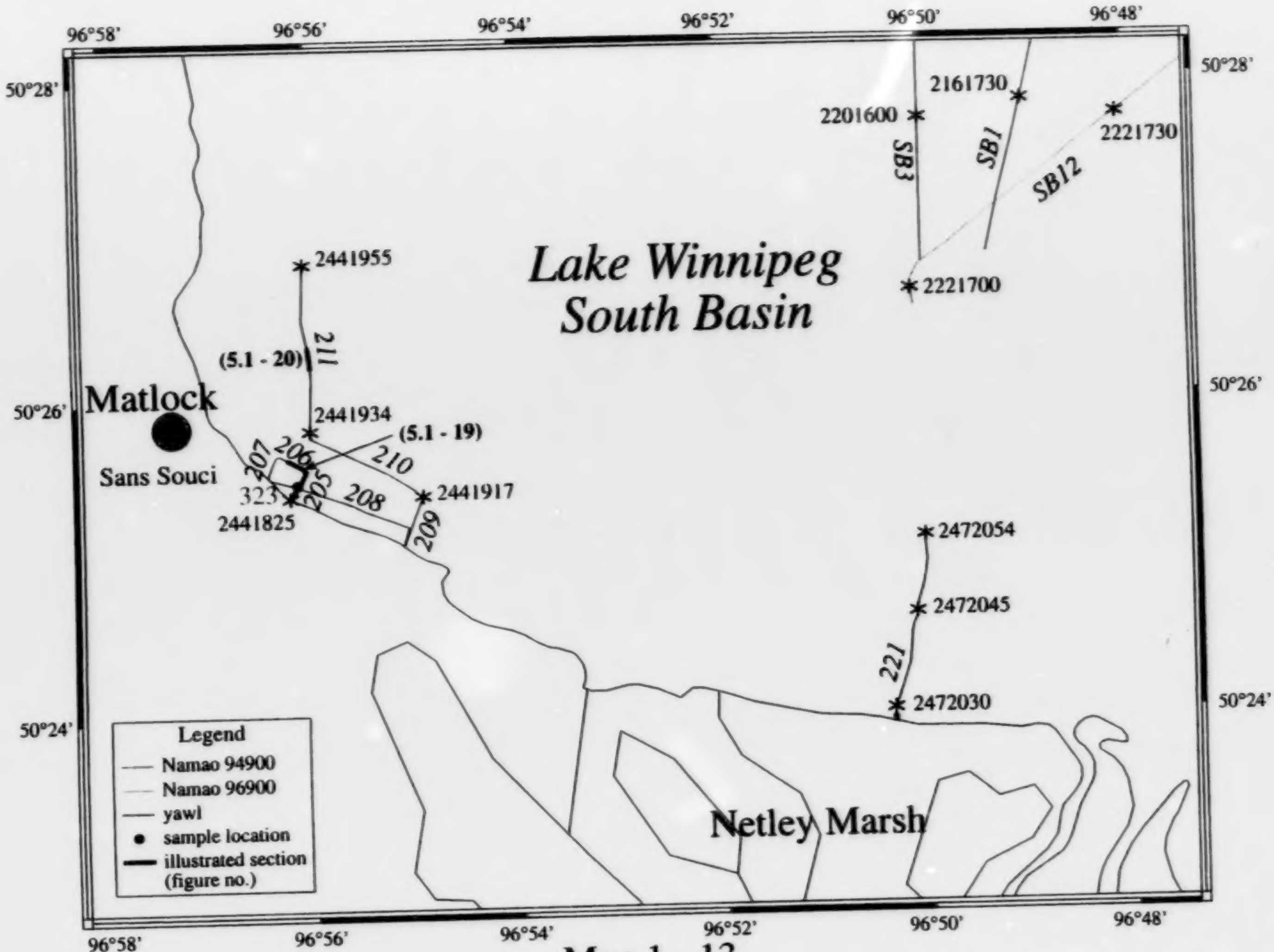
Map 1 - 10


97°24'
97°22'
97°20'
Marchand Point
Legend
yawl
illustrated section (figure no.)
52°50'
52°50'
2391520
2391533
196
(5.1 - 8)
52°48'
52°48'
Lake Winnipeg North Basin
97°24'
97°22'
97°20'

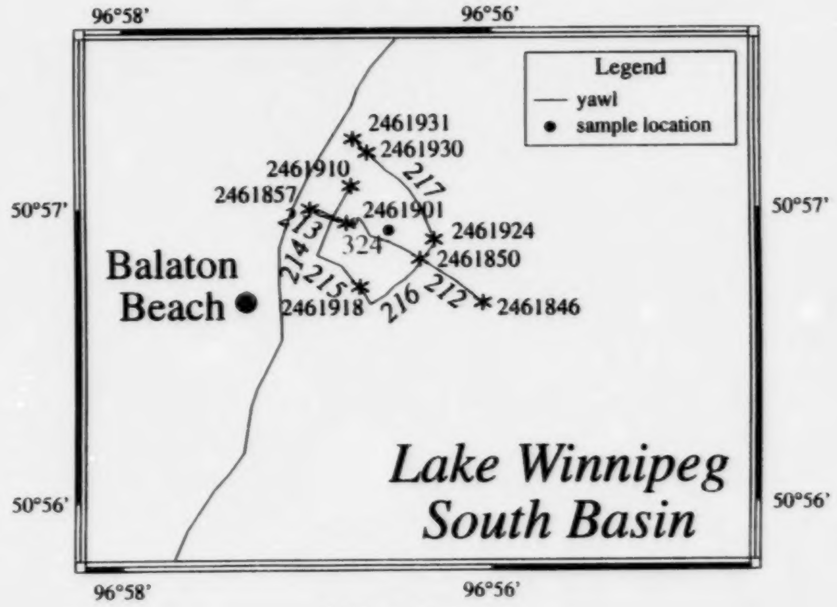
Map 1 - 11


96°52'
96°50'
Black Bear Island
Lake Winnipeg North Basin
NB7
2411813
2411711
201
198
51°46'
2411639
199
2411720
197
112
2411854
322
2411700
2411900
111
2411730
200
2411751
203
2411920
204
NB7
The Narrows
West Doghead Point
51°44'
Legend
Namao 94900
yawl
● sample location
96°52'
96°50'

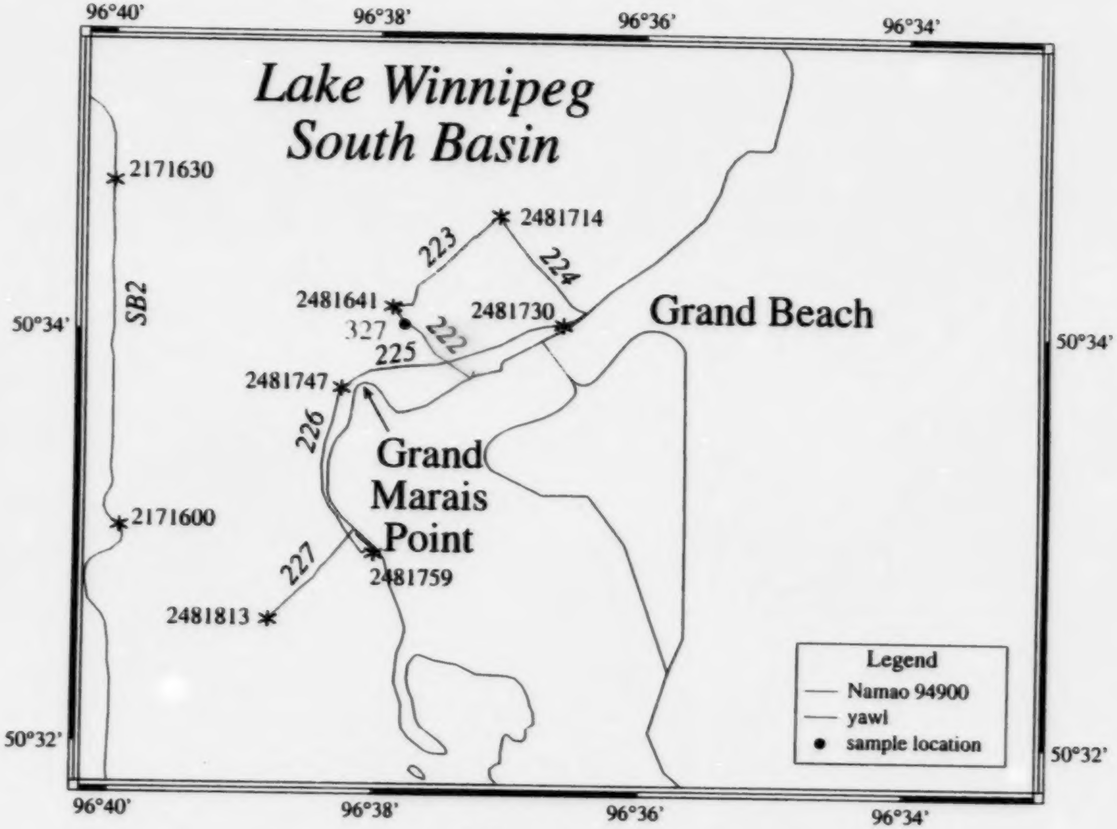
Map 1 - 12


96°58'
96°56'
96°54'
96°52'
96°50'
96°48'
50°28'
50°26'
50°24'
Lake Winnipeg
South Basin
2201600
2161730
2221730
SB3
SB1
SB12
2221700
2441955
211
(5.1 - 20)
Matlock
2441934
(5.1 - 19)
210
206
207
Sans Souci
205
323
208
2441917
2441825
209
2472054
2472045
221
2472030
Netley Marsh
Legend
Namao 94900
Namao 96900
yawl
sample location
illustrated section
(figure no.)

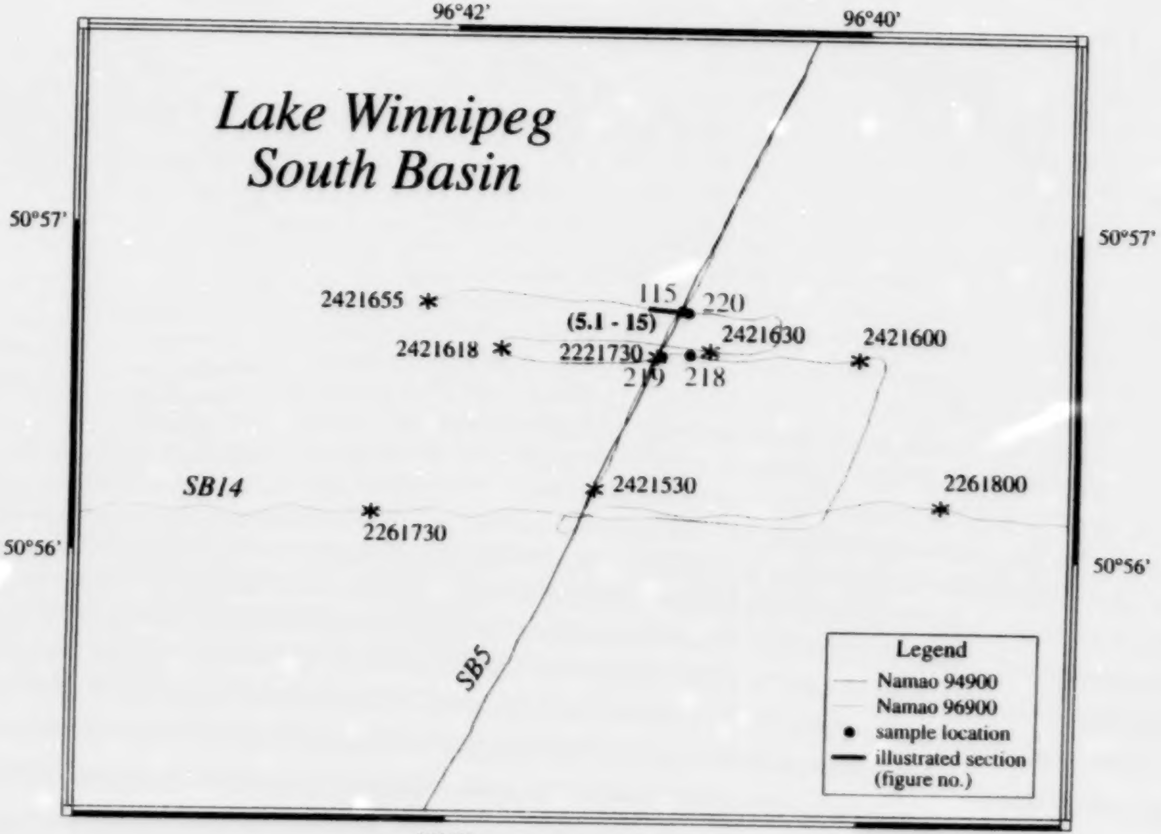
Map 1 - 13


96°58'
96°56'
Legend
yawl
sample location
2461931
2461930
2461910
2461857
2461901
2461924
2461850
2461846
2461918
217
213
214
215
216
212
324
Balaton Beach
50°57'
50°56'
Lake Winnipeg South Basin

Map 1 - 14


Lake Winnipeg
South Basin
Grand Beach
Grand
Marais
Point
2171630
SB2
2171600
2481714
223
224
2481641
327
222
2481730
225
2481747
226
227
2481759
2481813
96°40'
96°38'
96°36'
96°34'
50°34'
50°32'
Legend
Namao 94900
yawl
sample location

Map 1 - 15


96°42'
96°40'
Lake Winnipeg
South Basin
50°57'
50°57'
2421655
115
220
(5.1 - 15)
2421618
2221730
2421630
2421600
219
218
SB14
2421530
2261800
2261730
50°56'
50°56'
SB5
Legend
Namao 94900
Namao 96900
● sample location
illustrated section (figure no.)
96°42'
96°40'

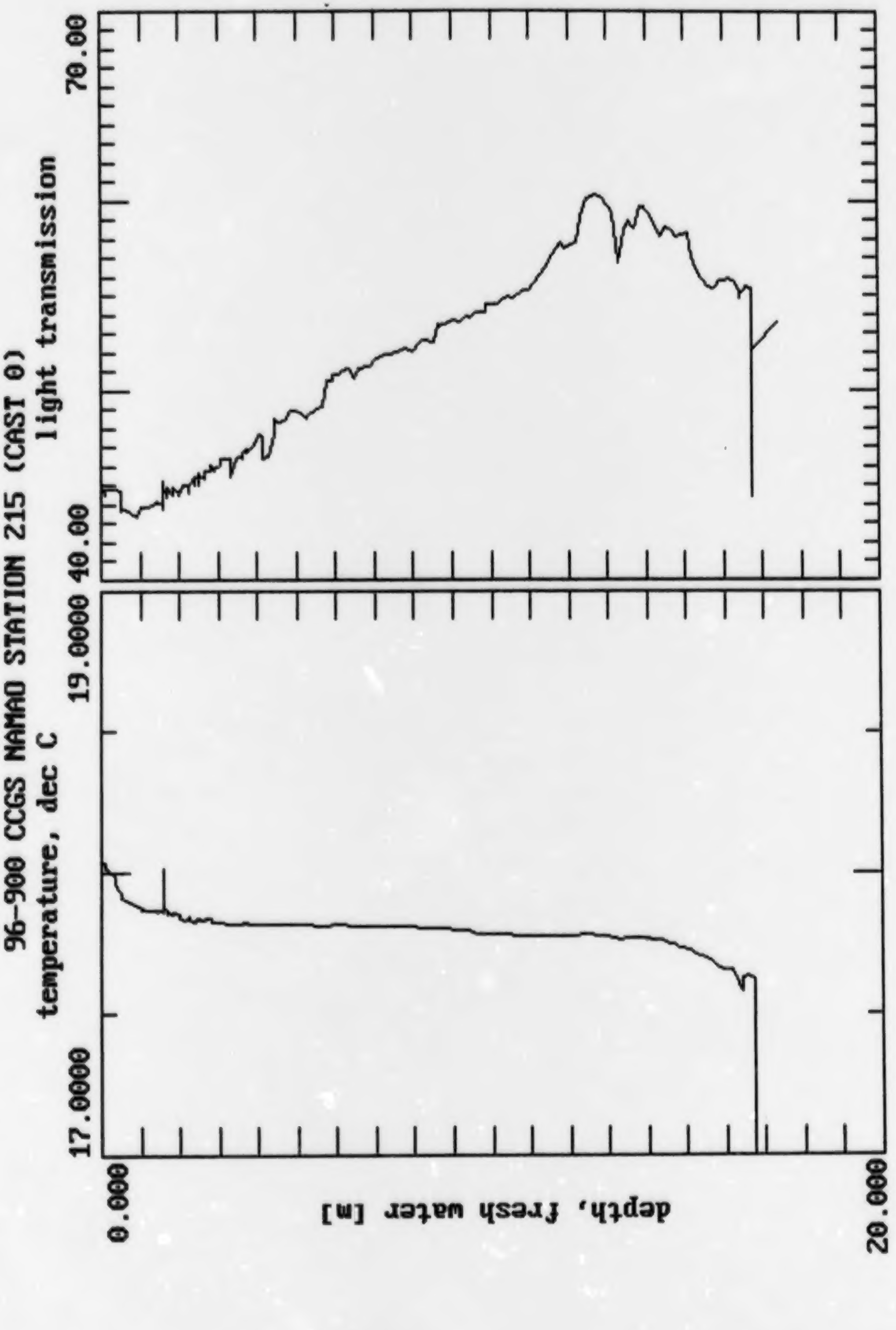
Pearson Reef Detail

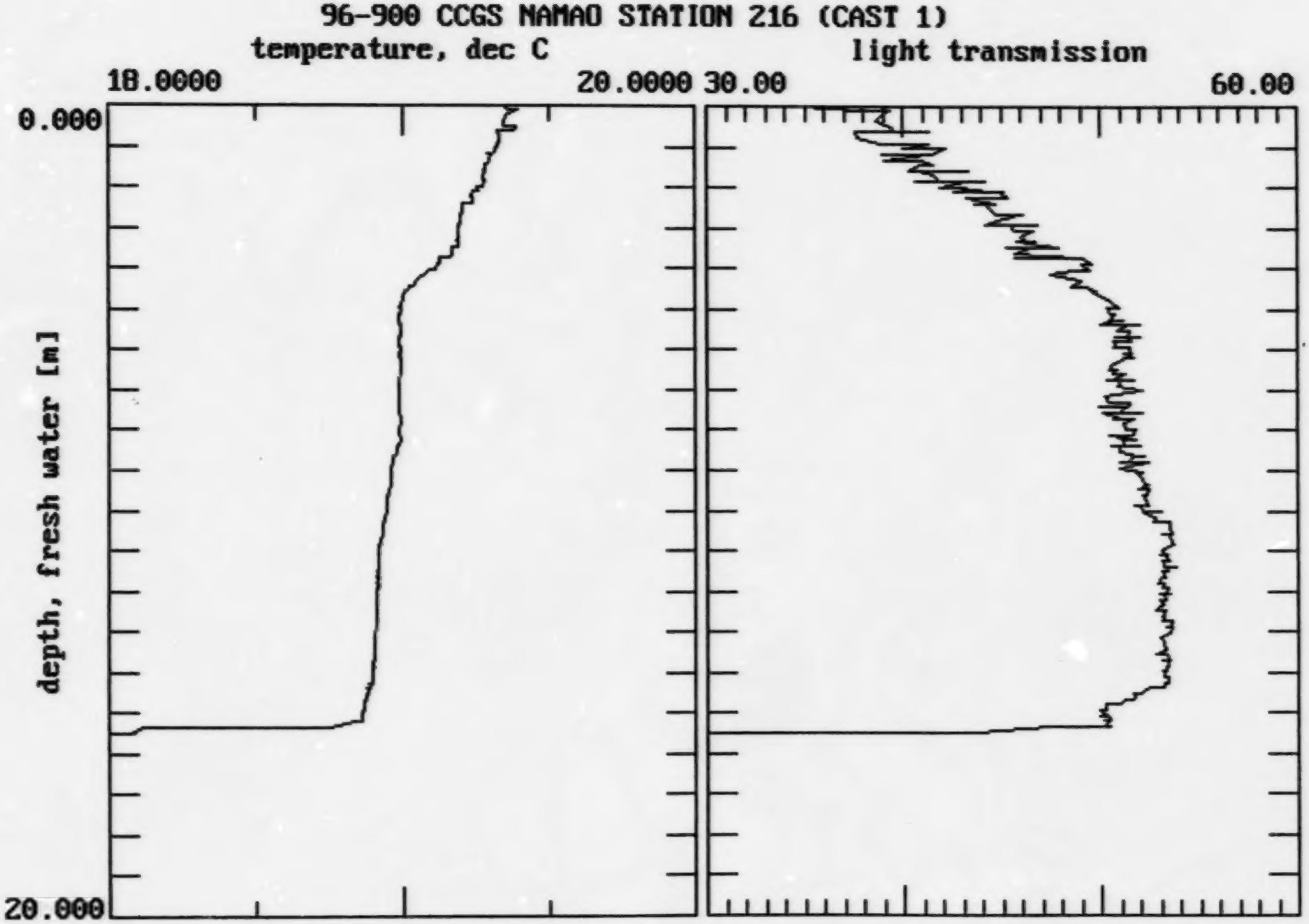
Appendix 10.2

Lake Winnipeg Project CTD profiles

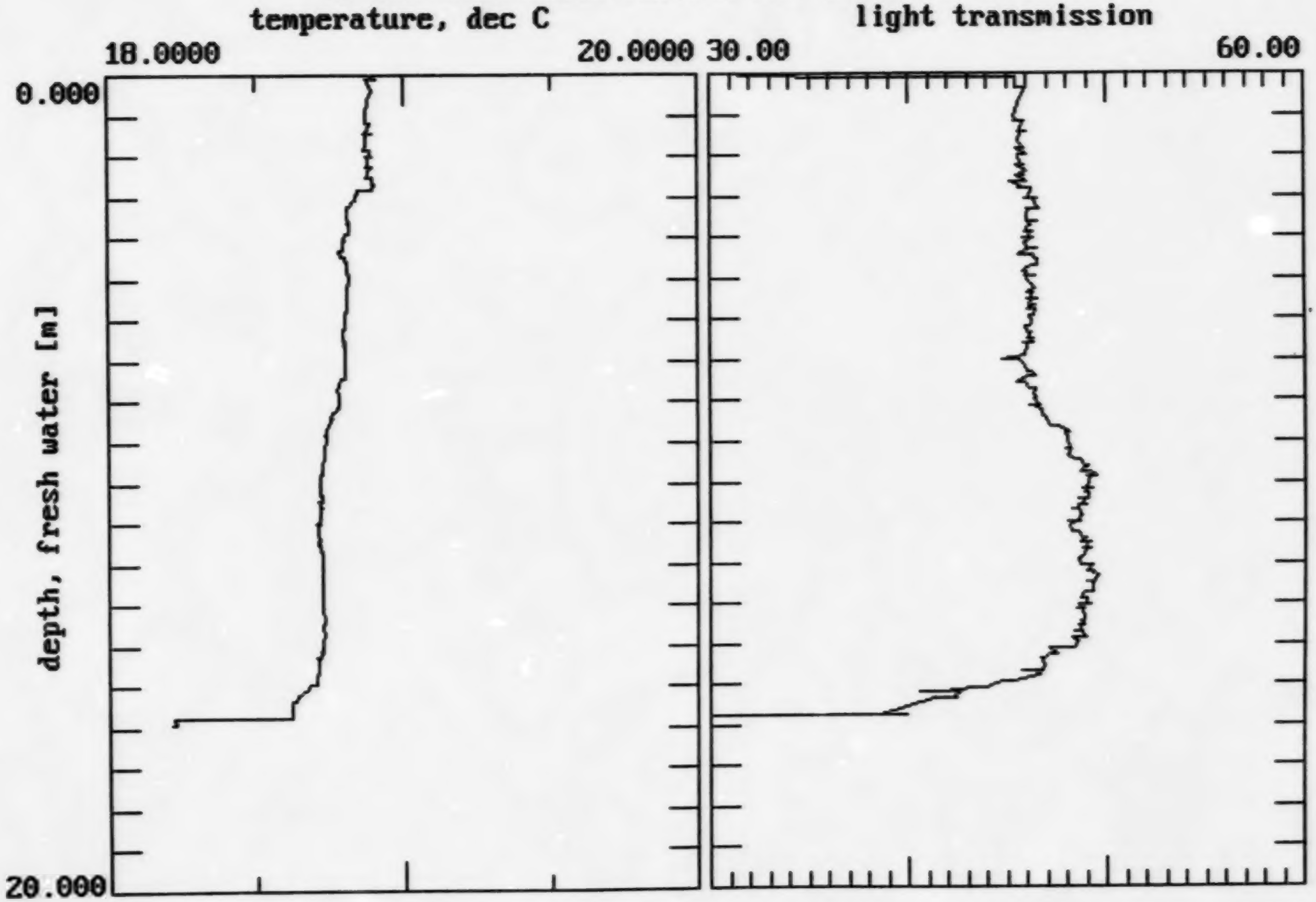
K.W. Asprey

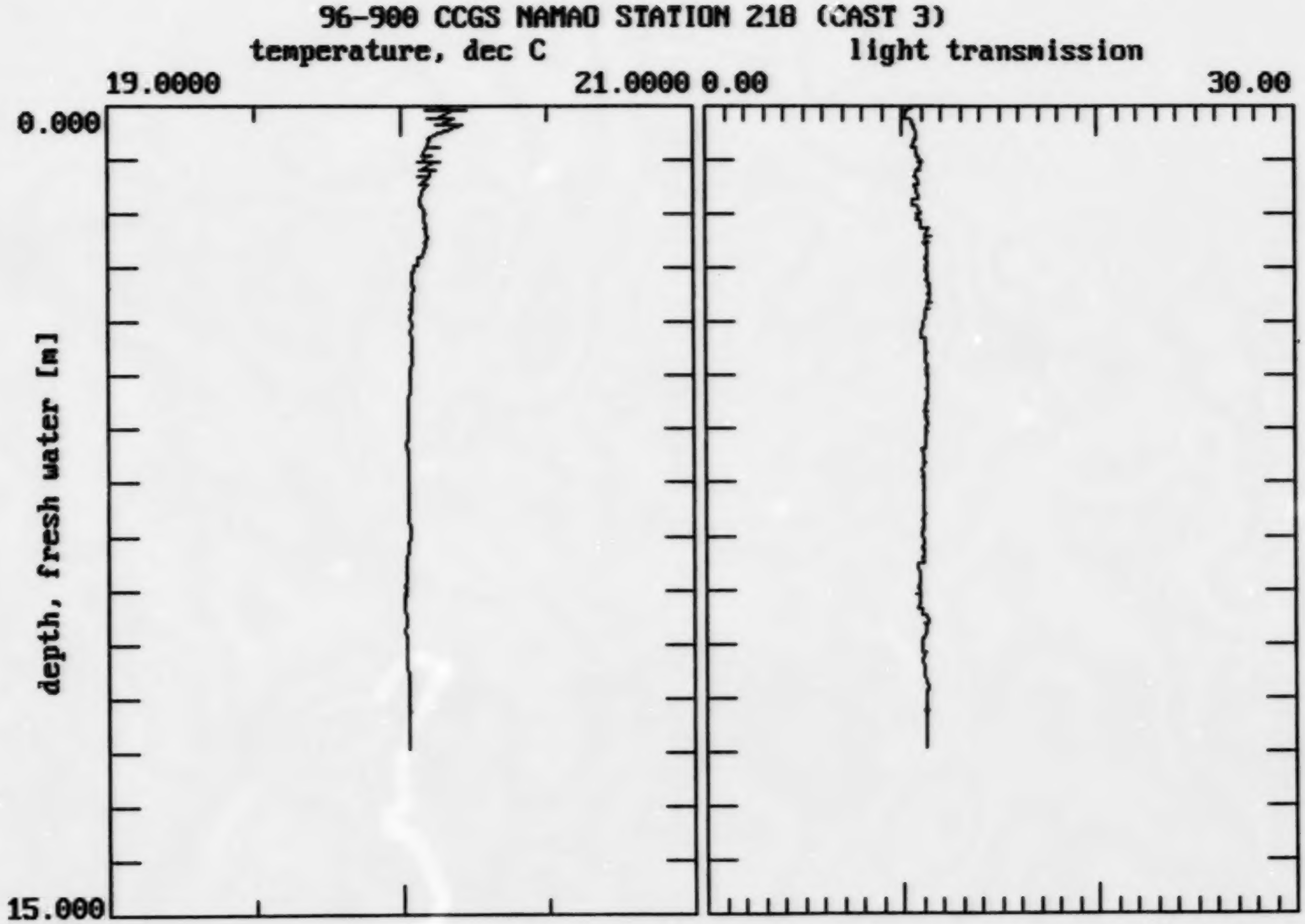
Geological Survey of Canada (Atlantic)

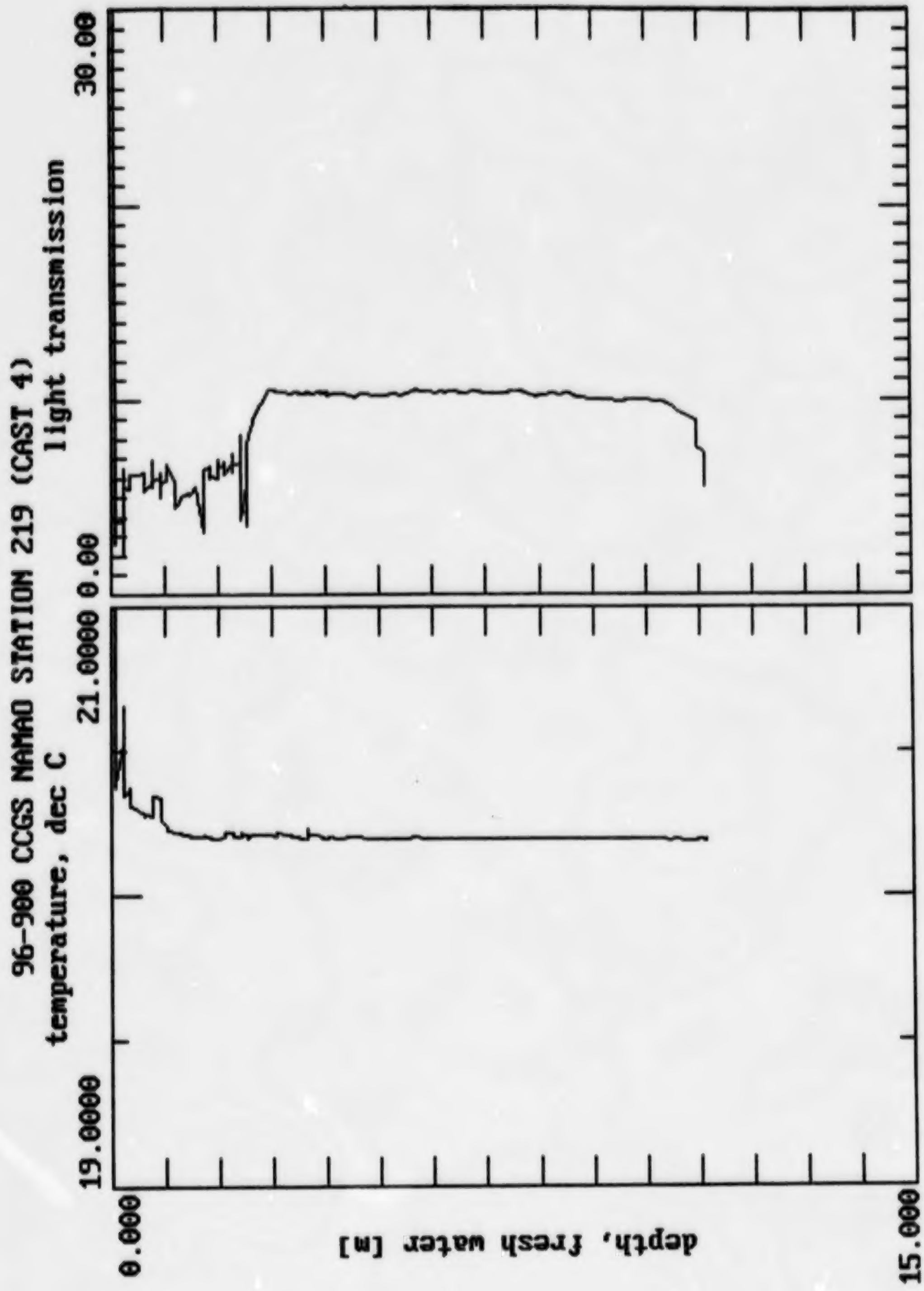

96-900 CCGS NAMAO STATION 215 (CAST 0)
light transmission
40.00
70.00
temperature, dec C
17.0000
19.0000
depth, fresh water [m]
0.000
20.000


96-900 CCGS NAMAO STATION 216 (CAST 1)
temperature, dec C
light transmission
18.0000
20.0000
30.00
60.00
0.000
20.000
depth, fresh water [m]

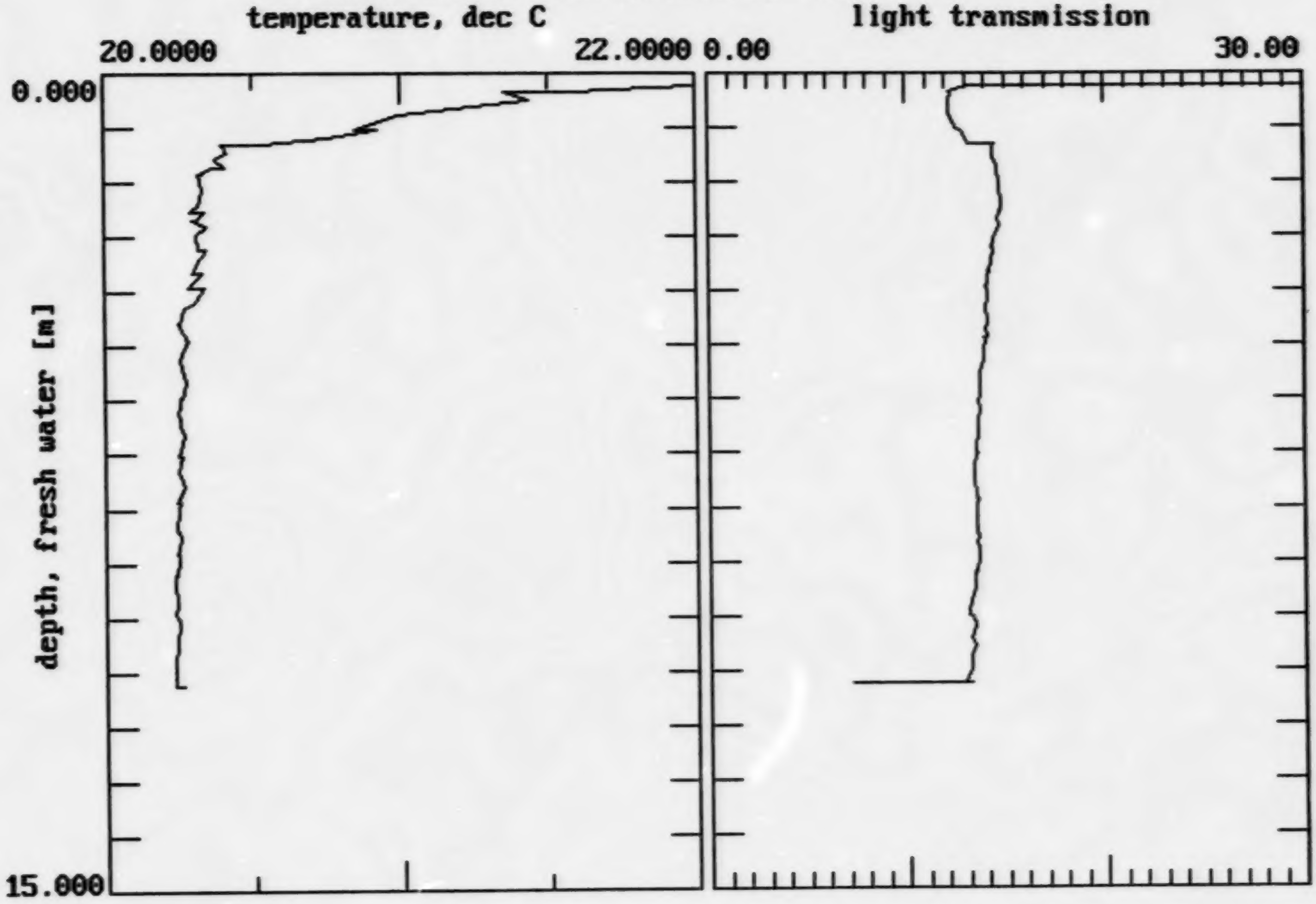
96-900 CCGS NAMAD STATION 217 (CAST 2)

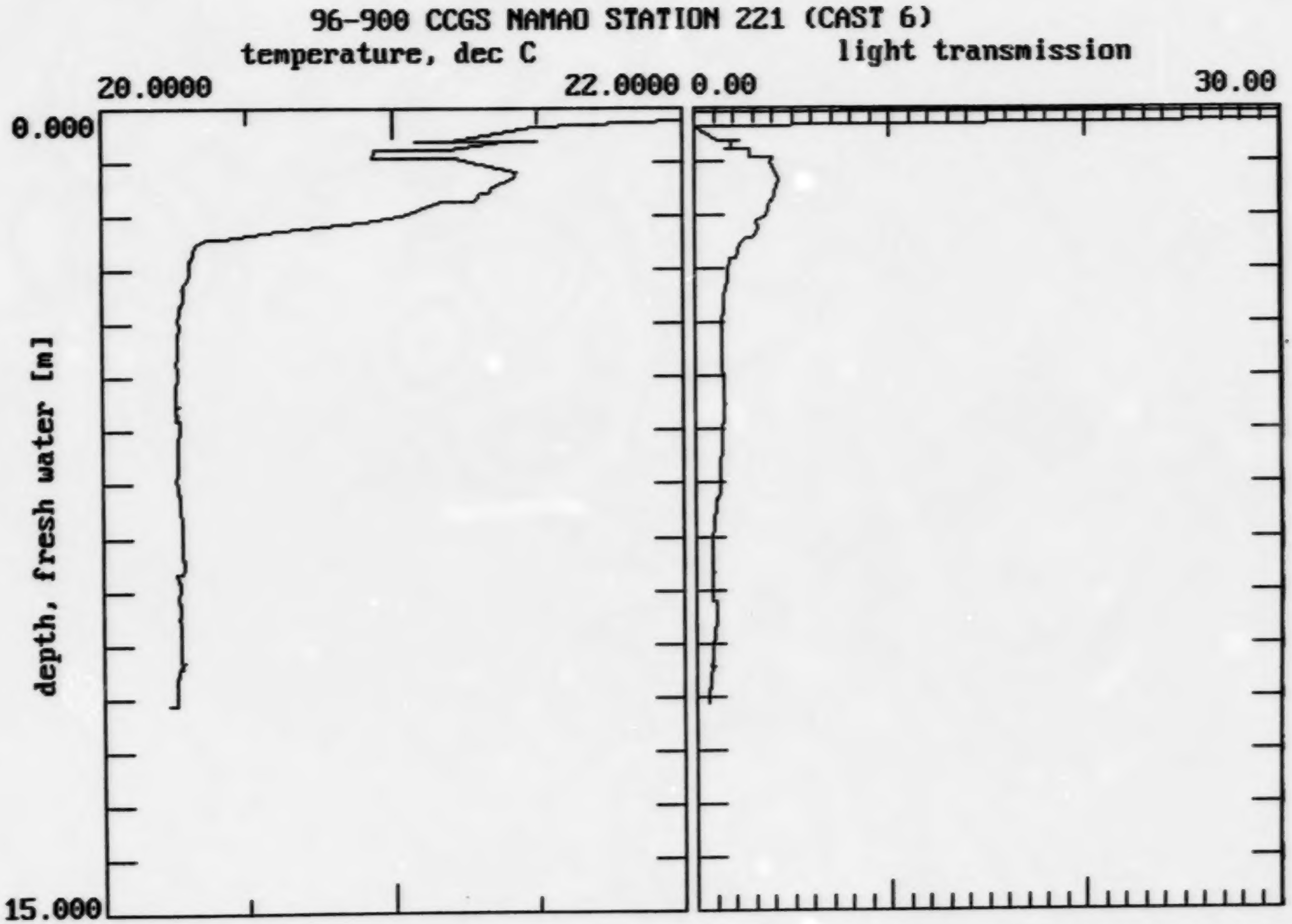



96-900 CCGS NAMAO STATION 218 (CAST 3)
temperature, dec C
light transmission
19.0000
21.0000
0.00
30.00
0.000
15.000
depth, fresh water [m]

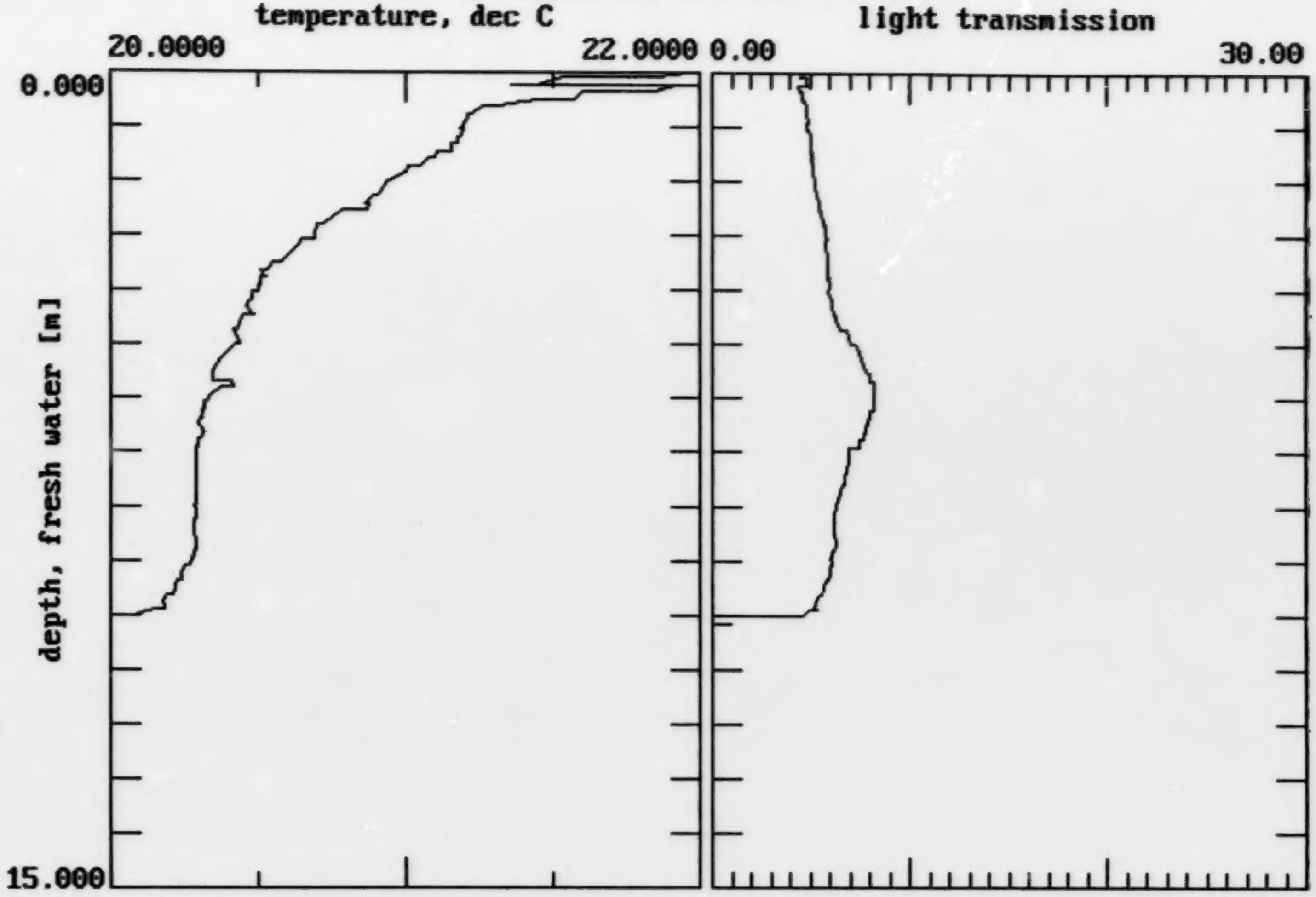

96-900 CCGS NAMAO STATION 219 (CAST 4)
temperature, dec C
light transmission
19.0000
21.0000
0.00
30.00
0.000
15.000
depth, fresh water [m]

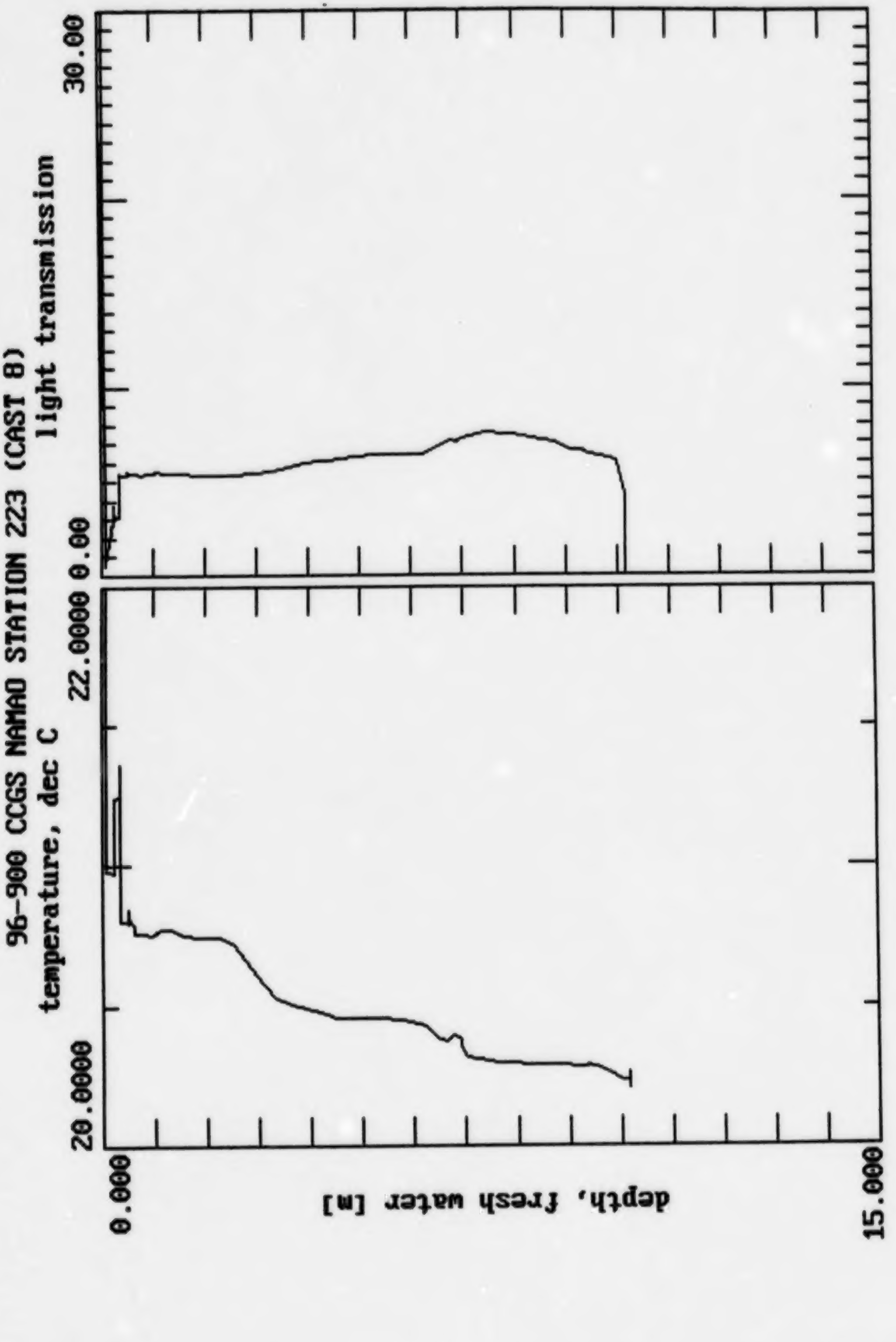
96-900 CCGS NAMAO STATION 220 (CAST 5)



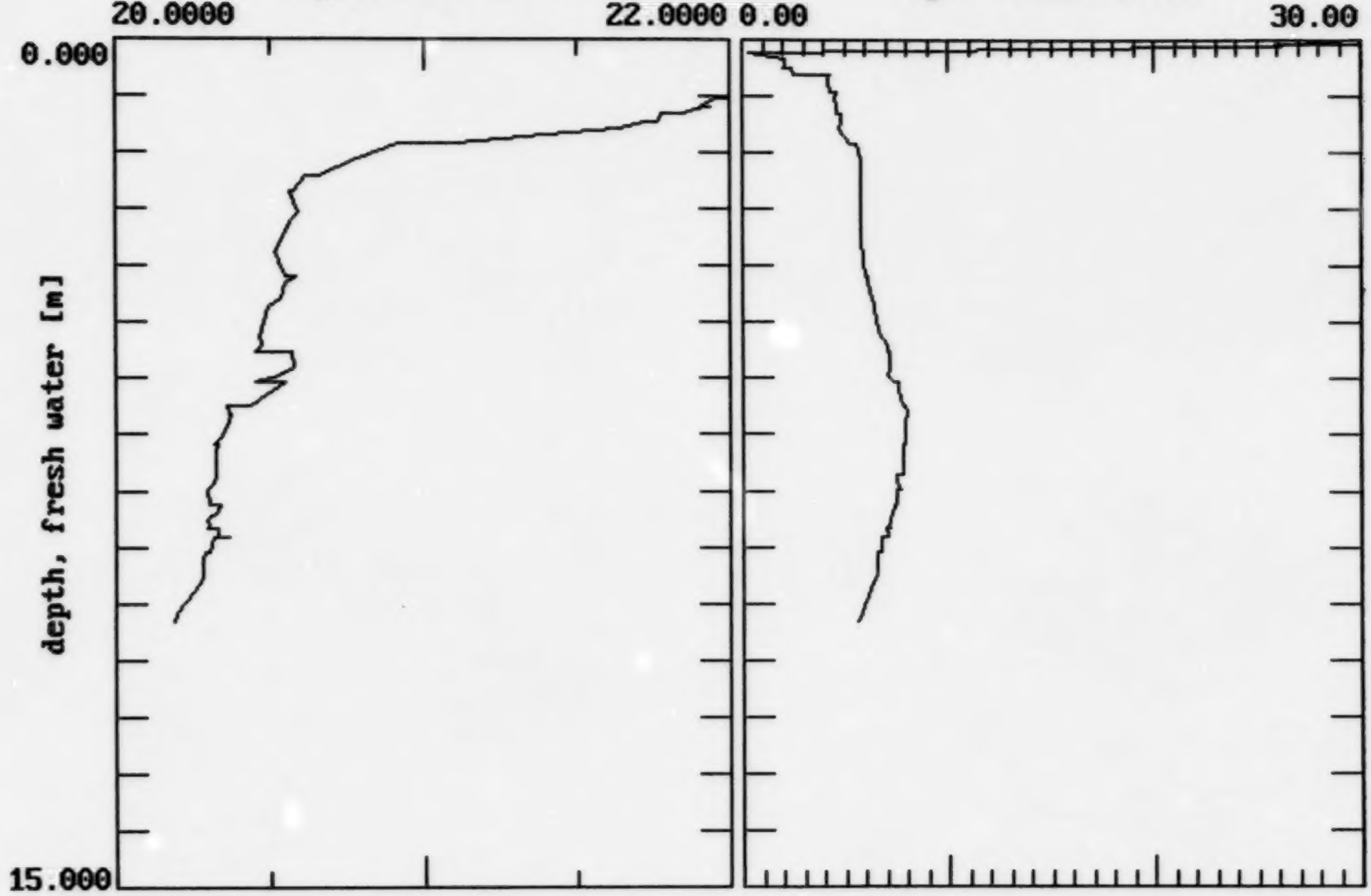

96-900 CCGS NAMAO STATION 221 (CAST 6)
temperature, dec C
light transmission
20.0000
22.0000
0.00
30.00
0.000
15.000
depth, fresh water [m]

96-900 CCGS NAMAO STATION 222 (CAST 7)




96-900 CCGS NAMAO STATION 223 (CAST 8)
temperature, dec C
light transmission
20.0000
22.0000
0.00
30.00
0.000
15.000
depth, fresh water [m]

96-900 CCGS NAMAO STATION 224 (CAST 9)



Appendix 10.3

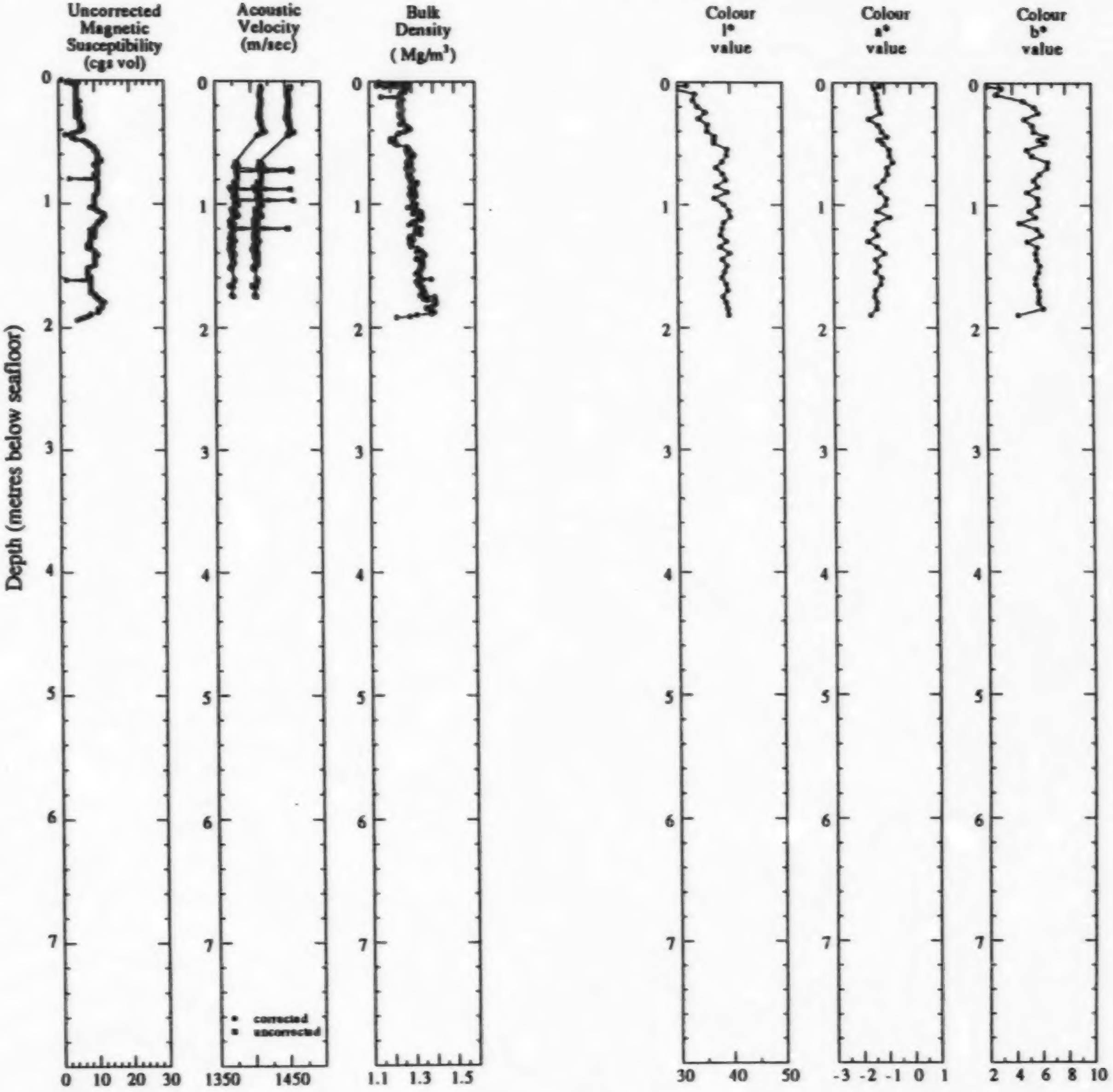
Downcore plots of Lake Winnipeg sediment physical properties

K. Jarrett

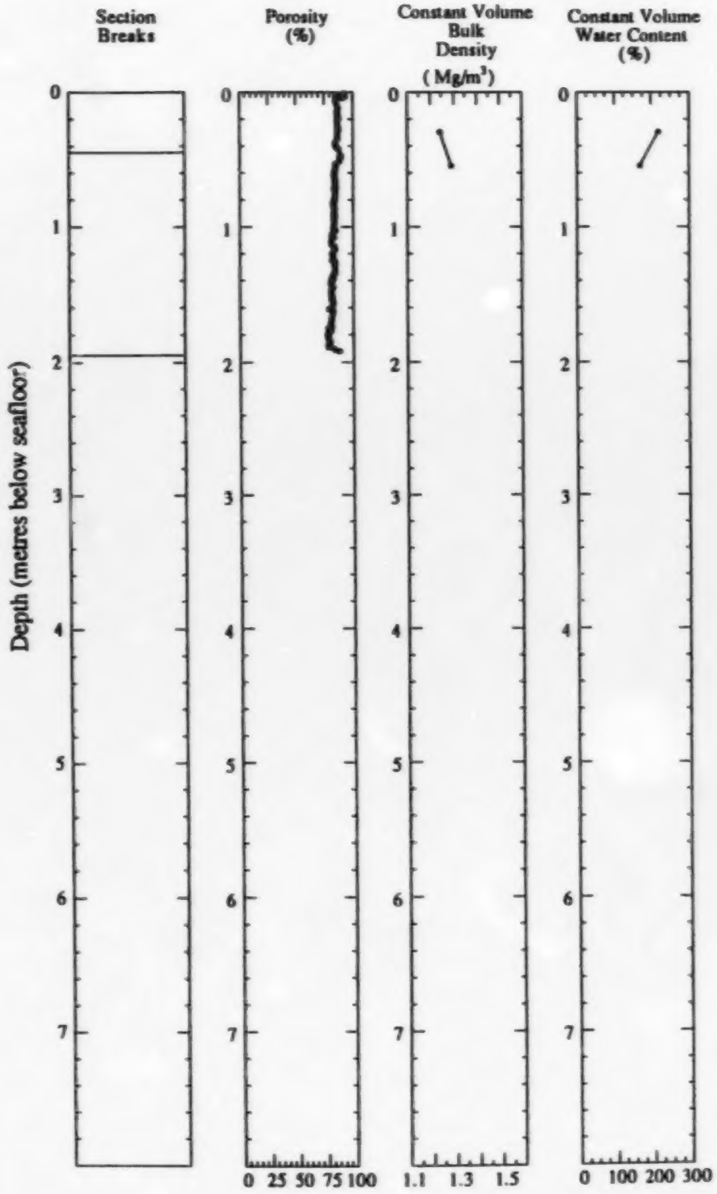
K&K Geoscience

PART 1

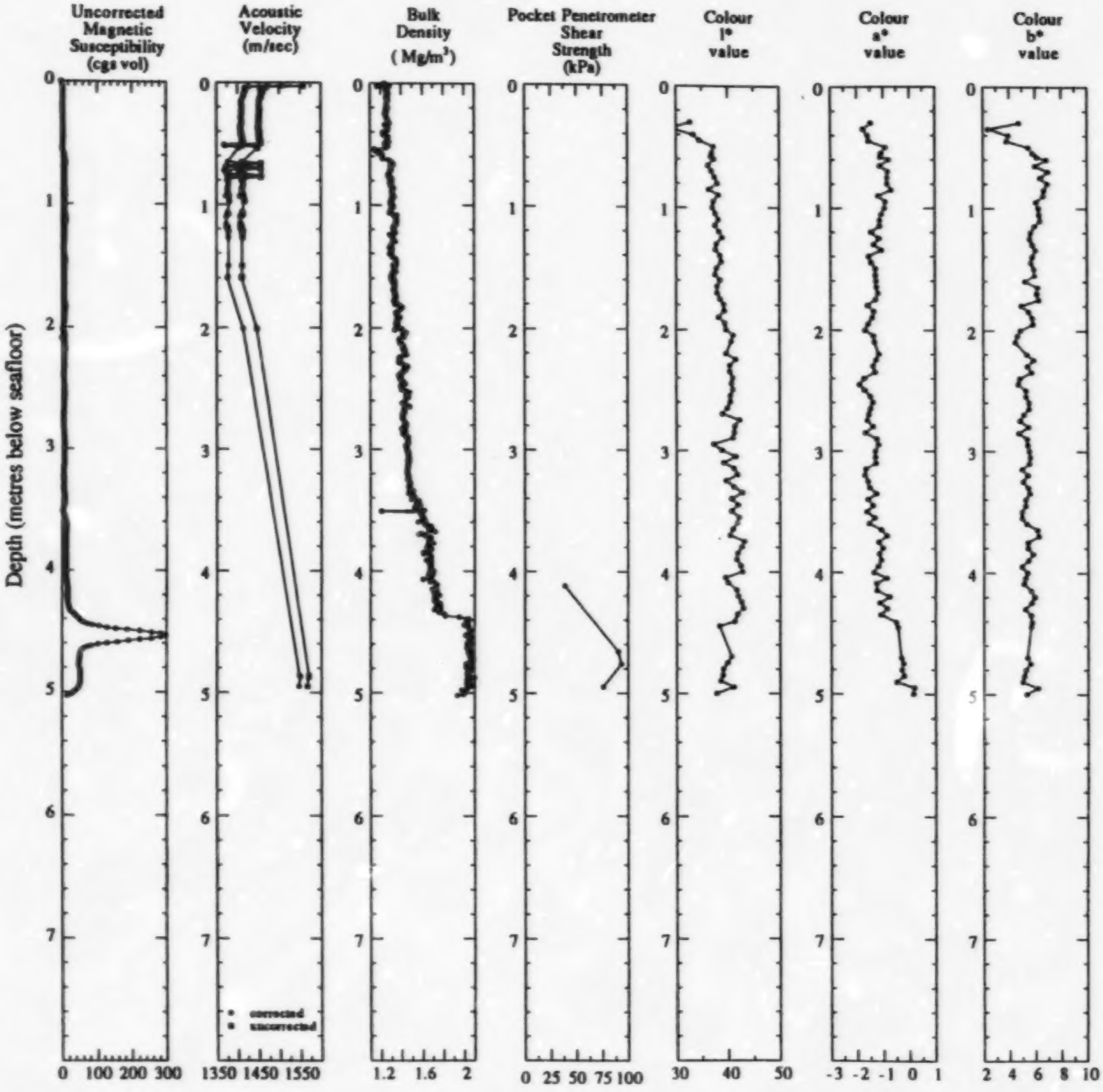
96900 Lake Winnipeg 201 gravity core



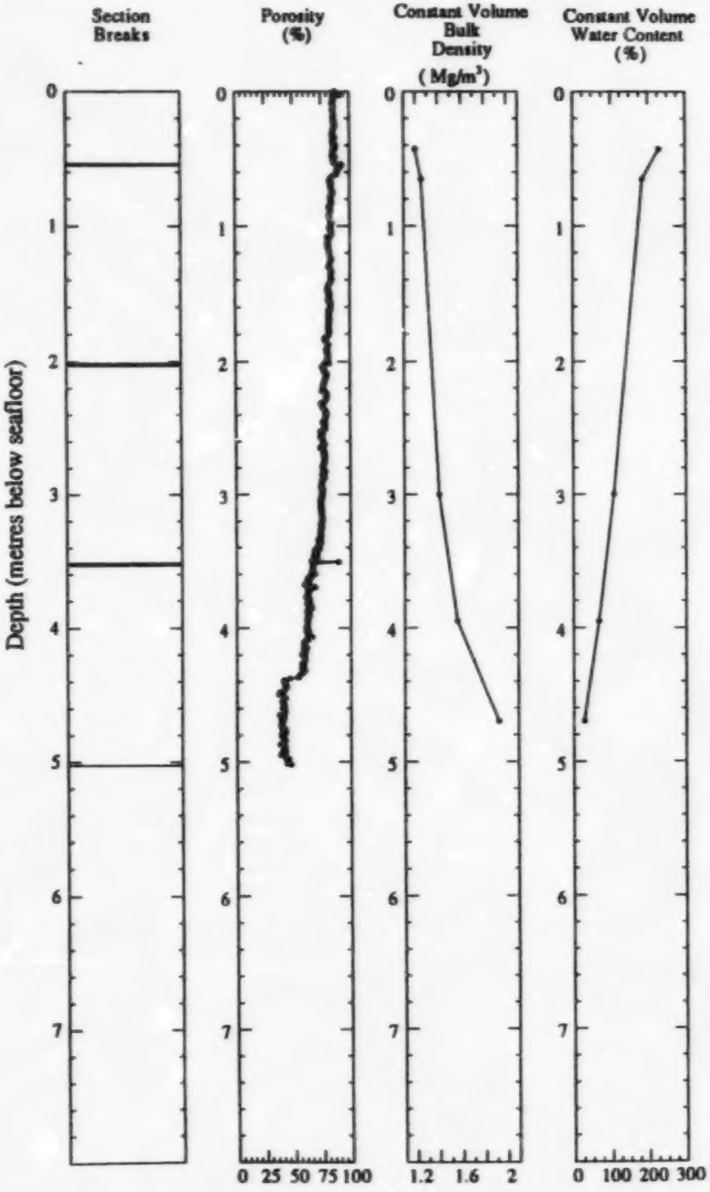
96900 Lake Winnipeg 201 gravity core



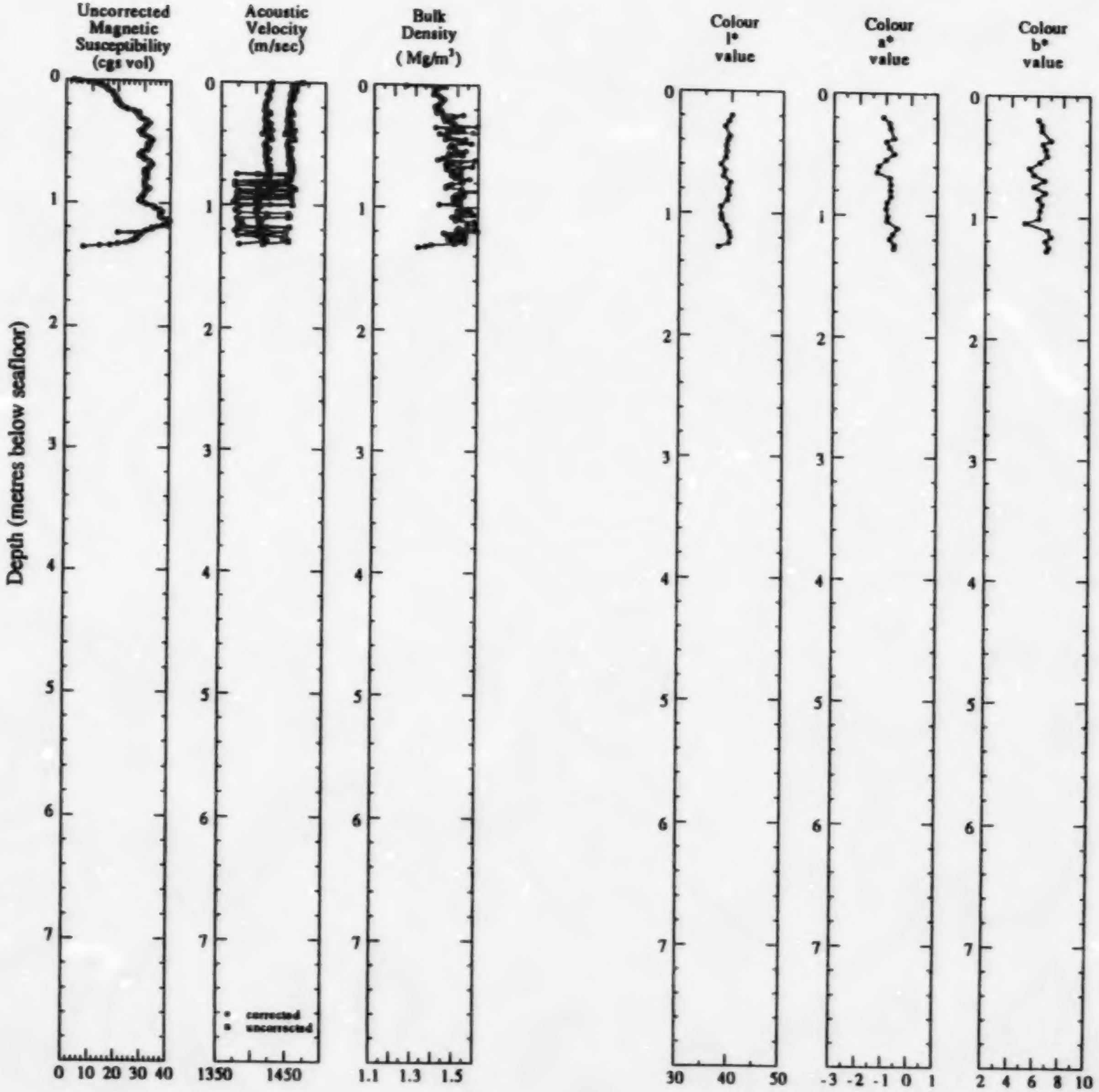
96900 Lake Winnipeg 201 piston core



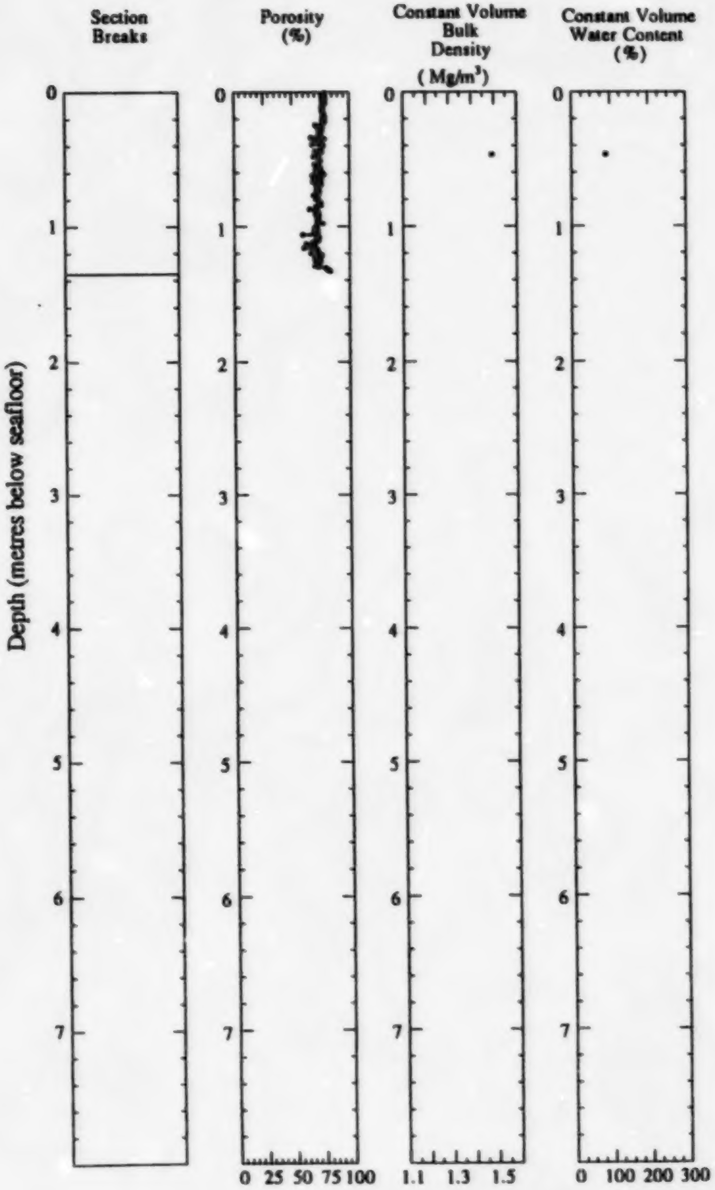
96900 Lake Winnipeg 201 piston core



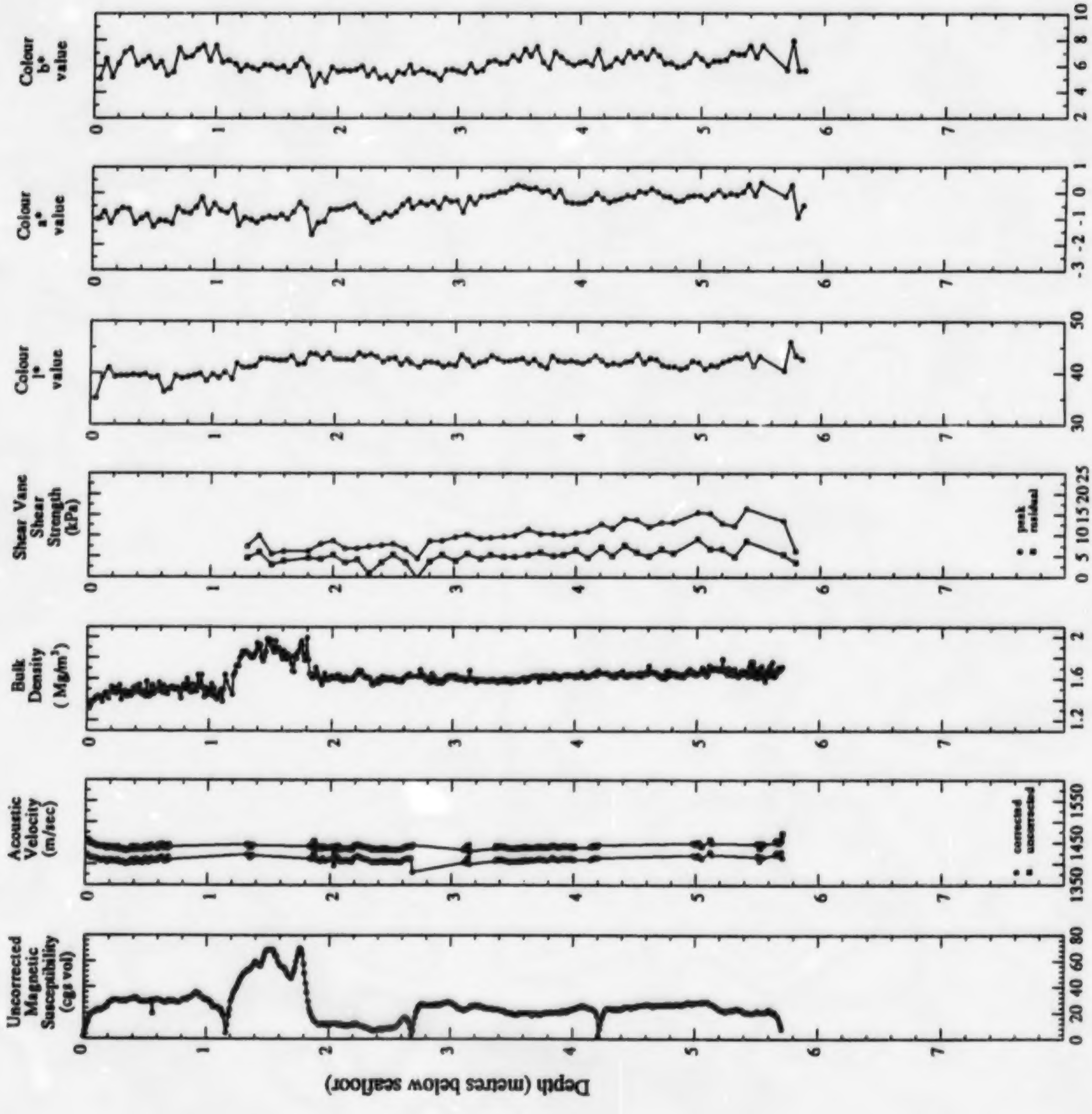
96900 Lake Winnipeg 202 gravity core



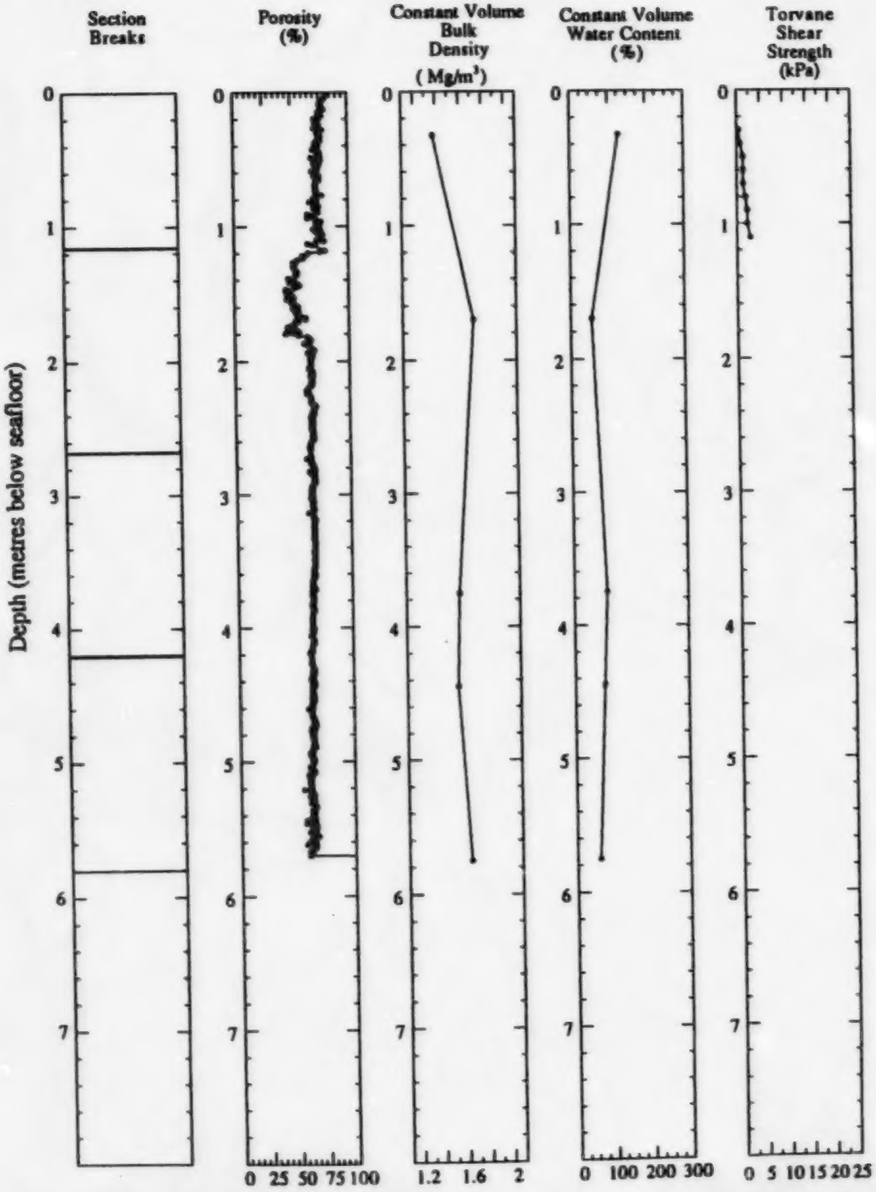
96900 Lake Winnipeg 202 gravity core



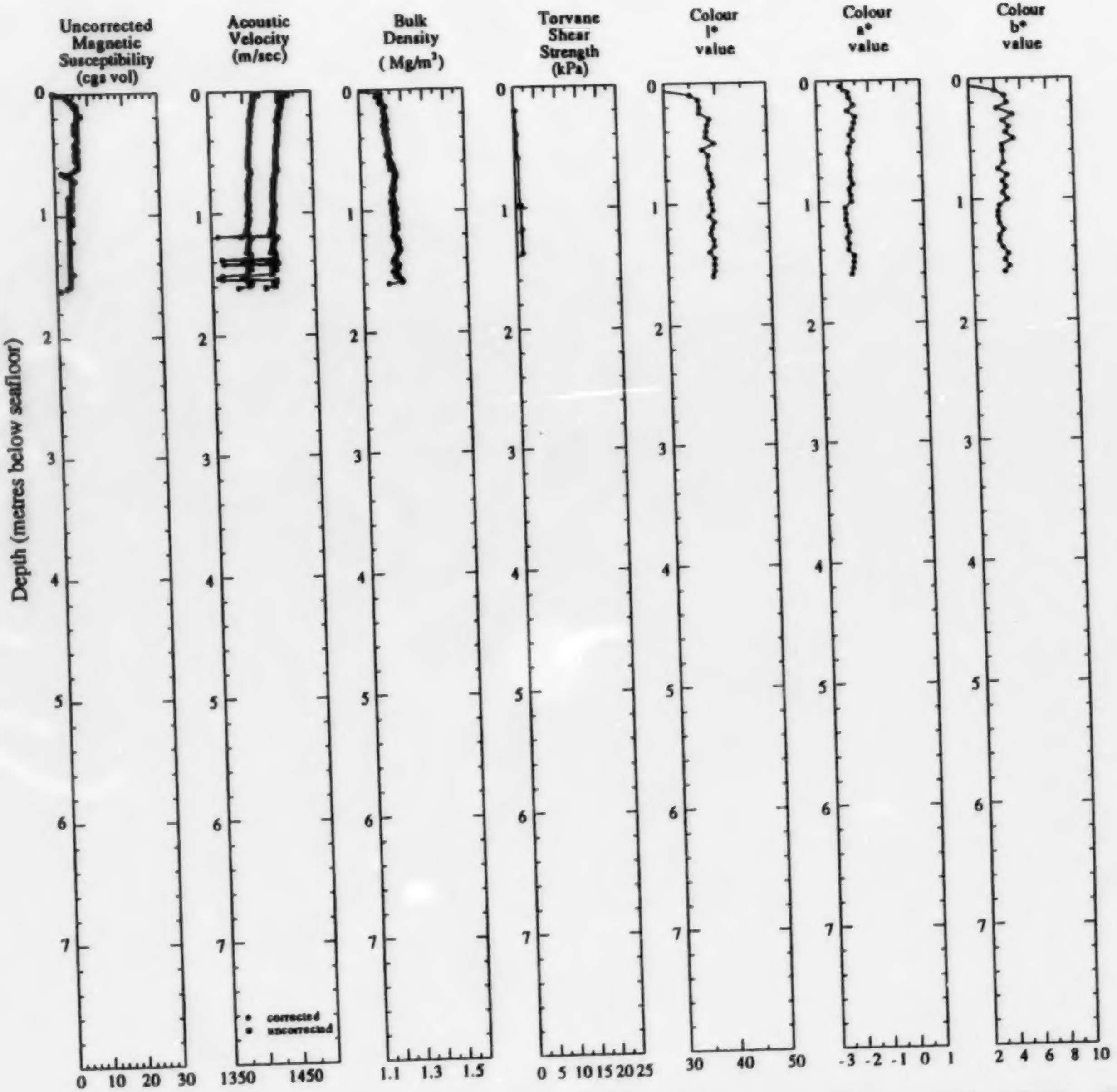
96900 Lake Winnipeg 202 piston core



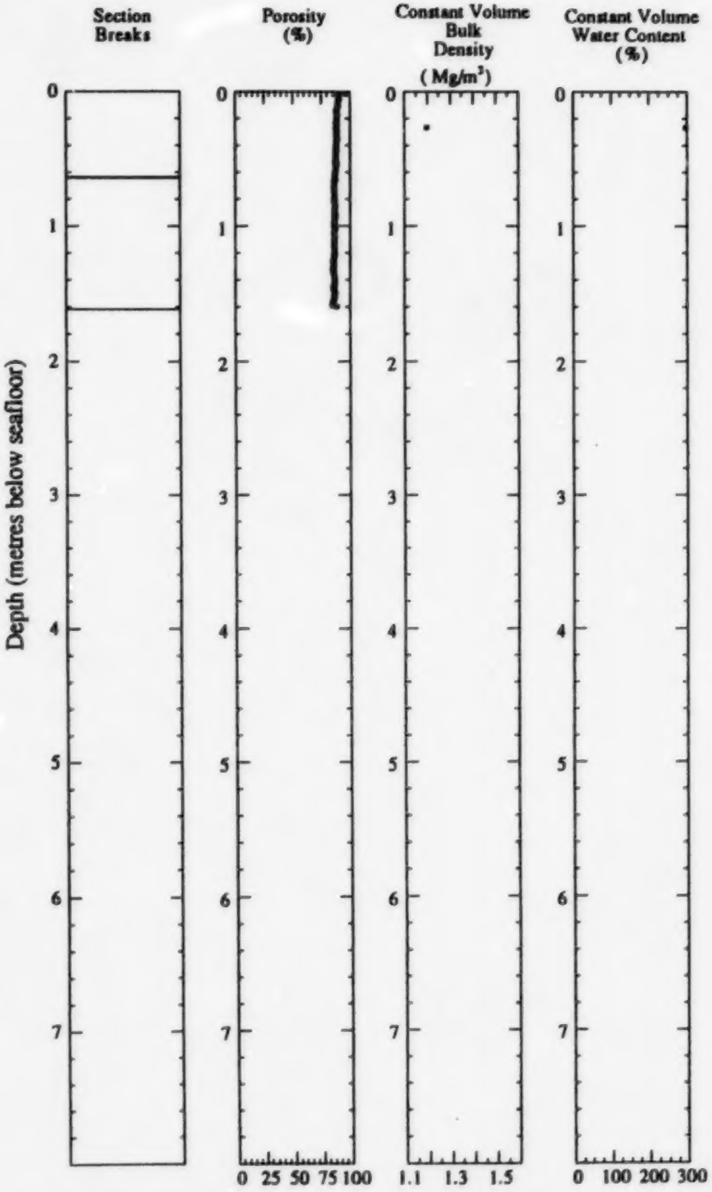
96900 Lake Winnipeg 202 piston core



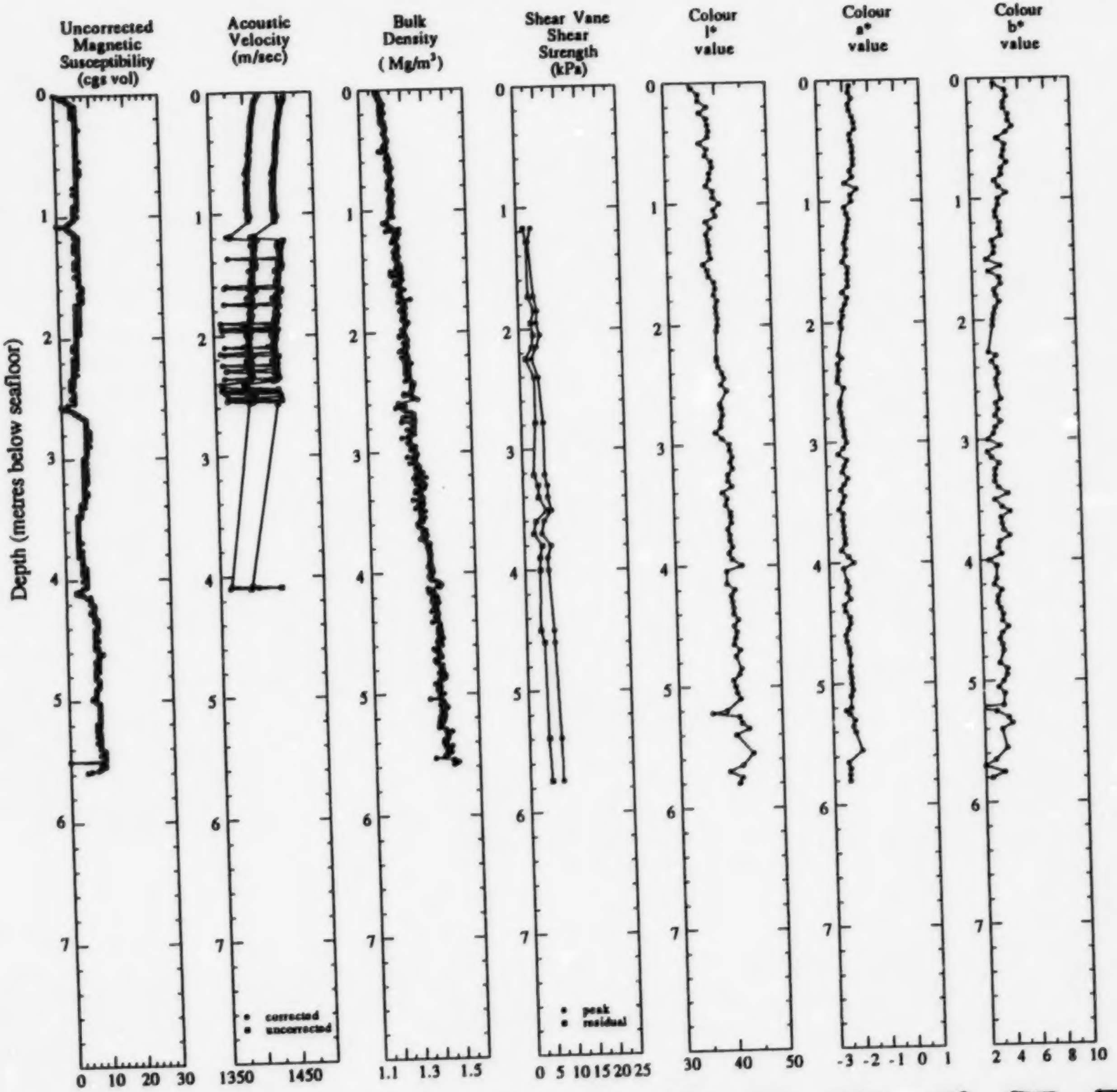
96900 Lake Winnipeg 203 gravity core



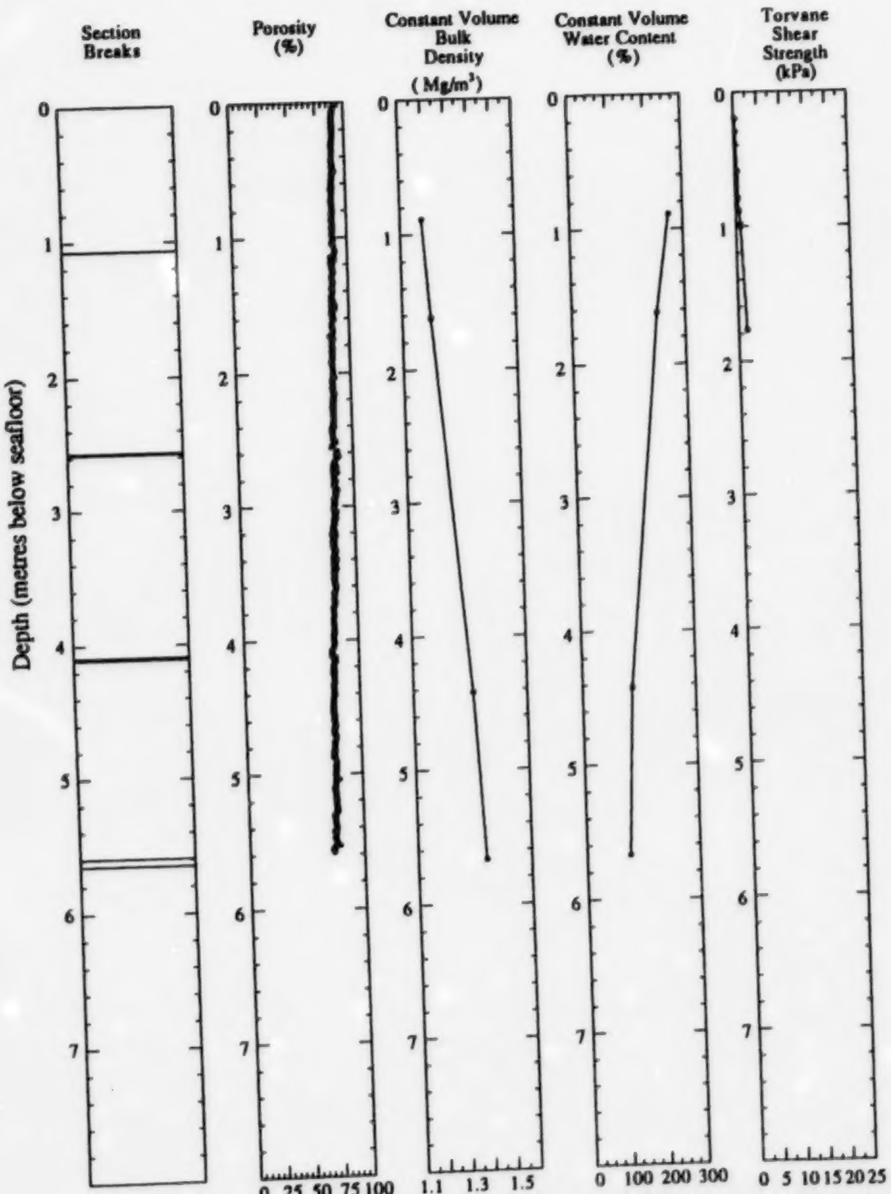
96900 Lake Winnipeg 203 gravity core



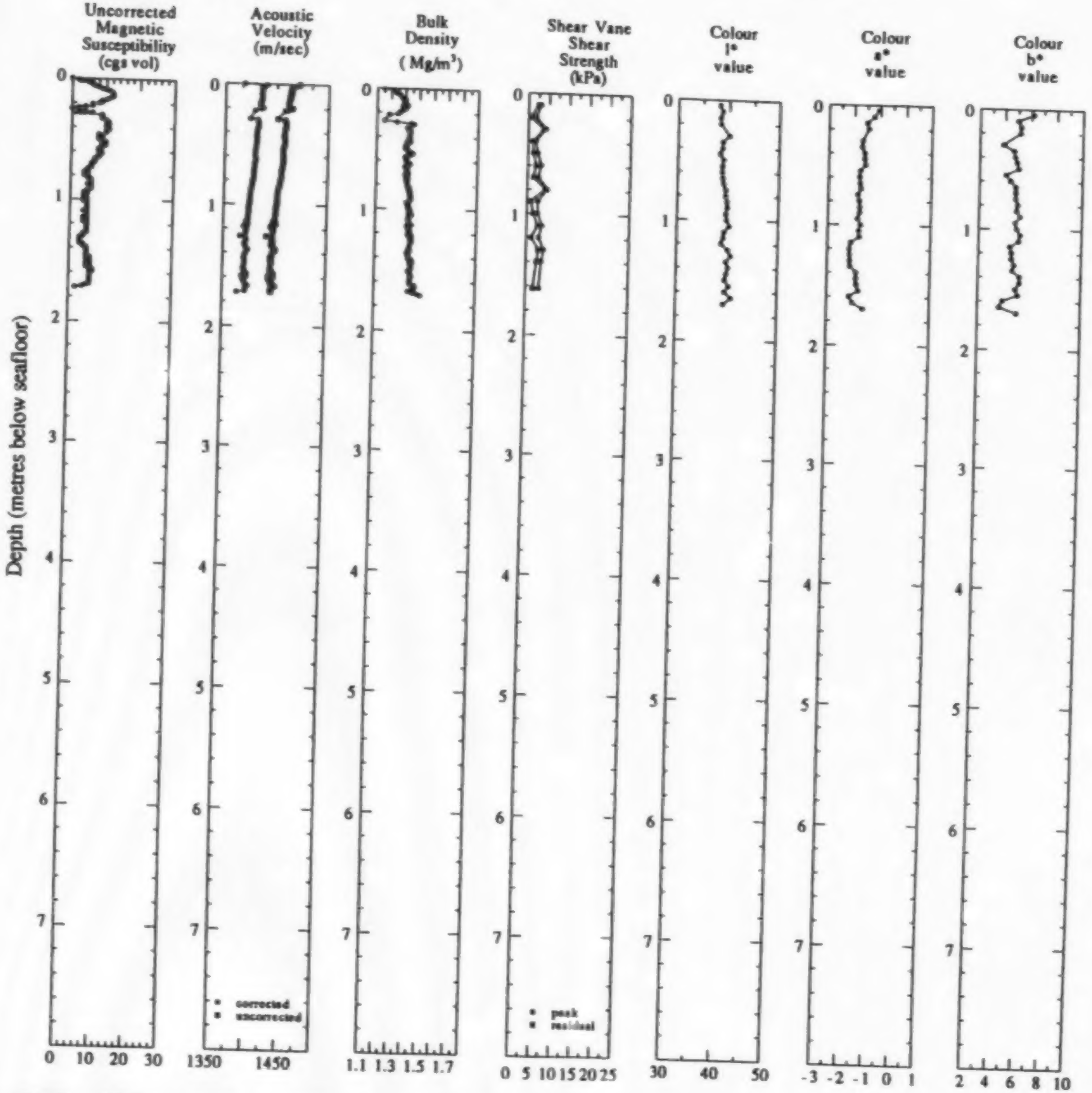
96900 Lake Winnipeg 203 piston core



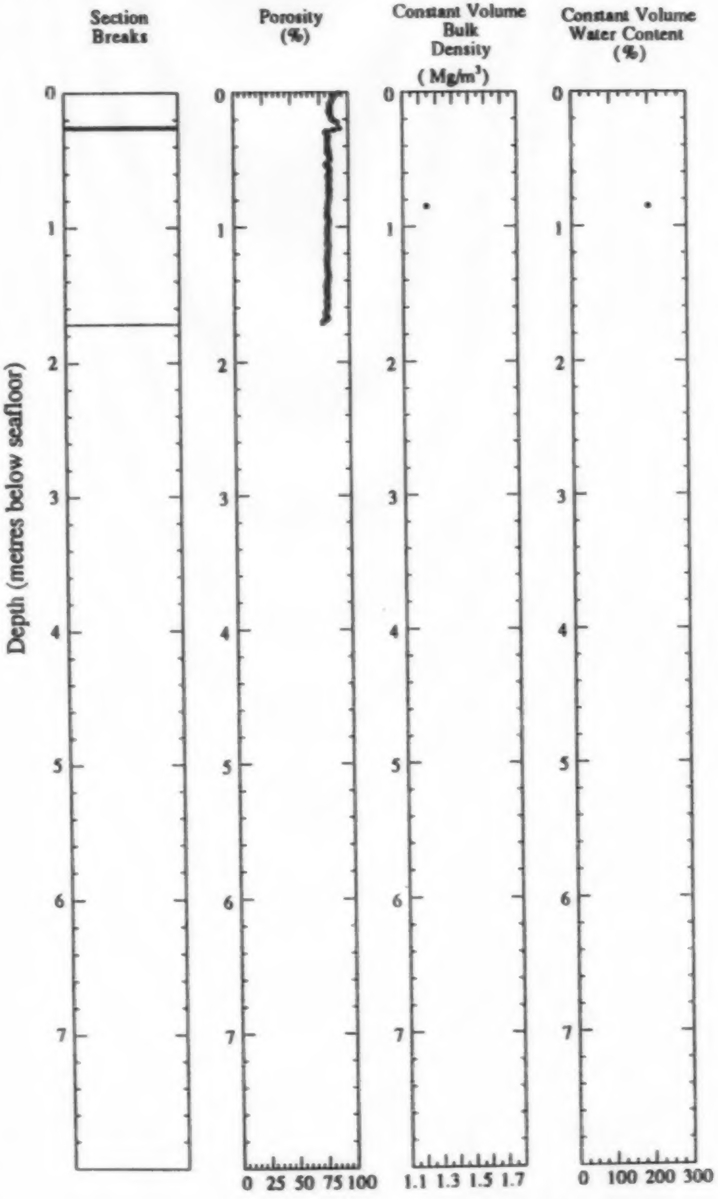
96900 Lake Winnipeg 203 piston core



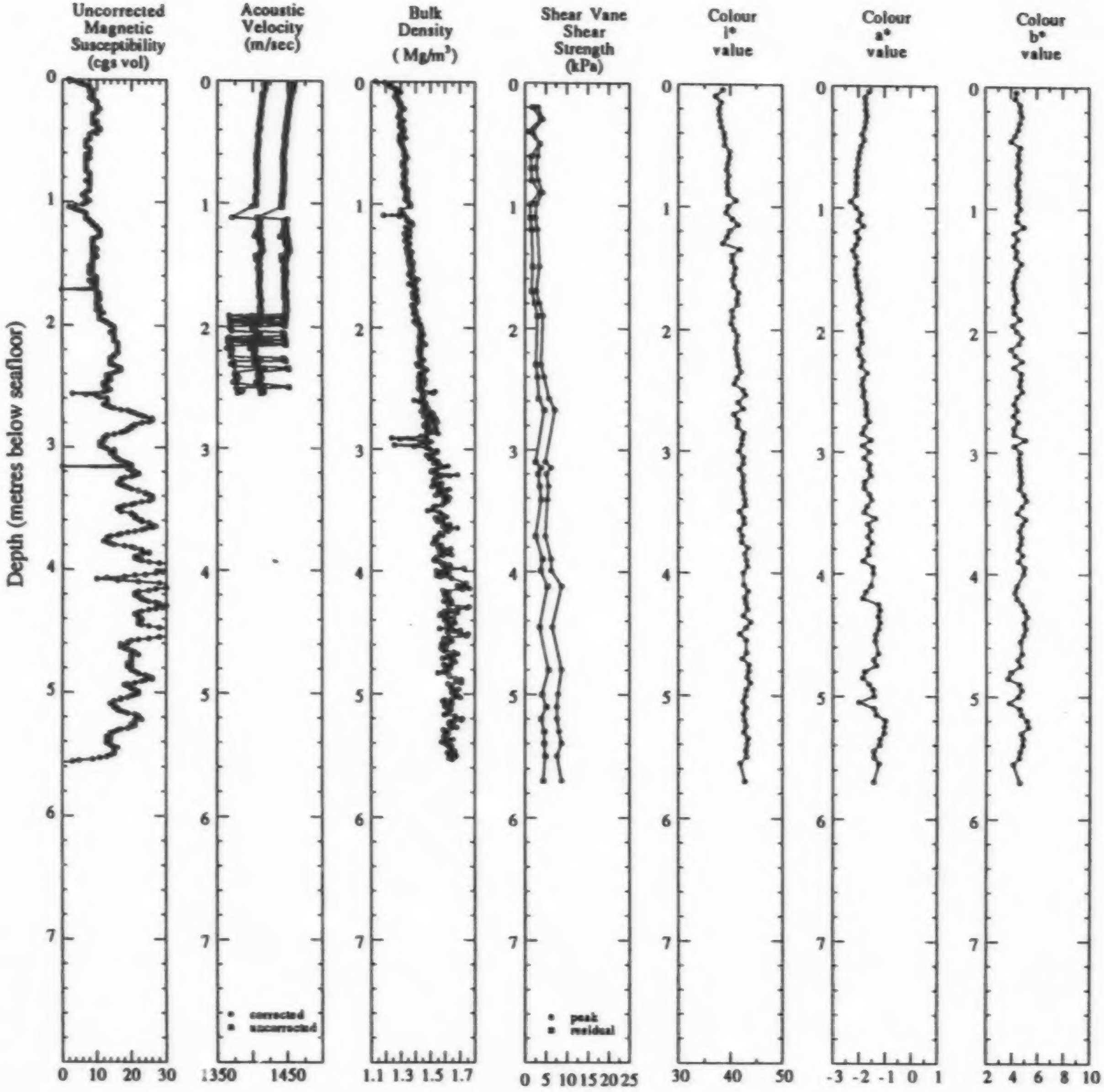
96900 Lake Winnipeg 204 gravity core



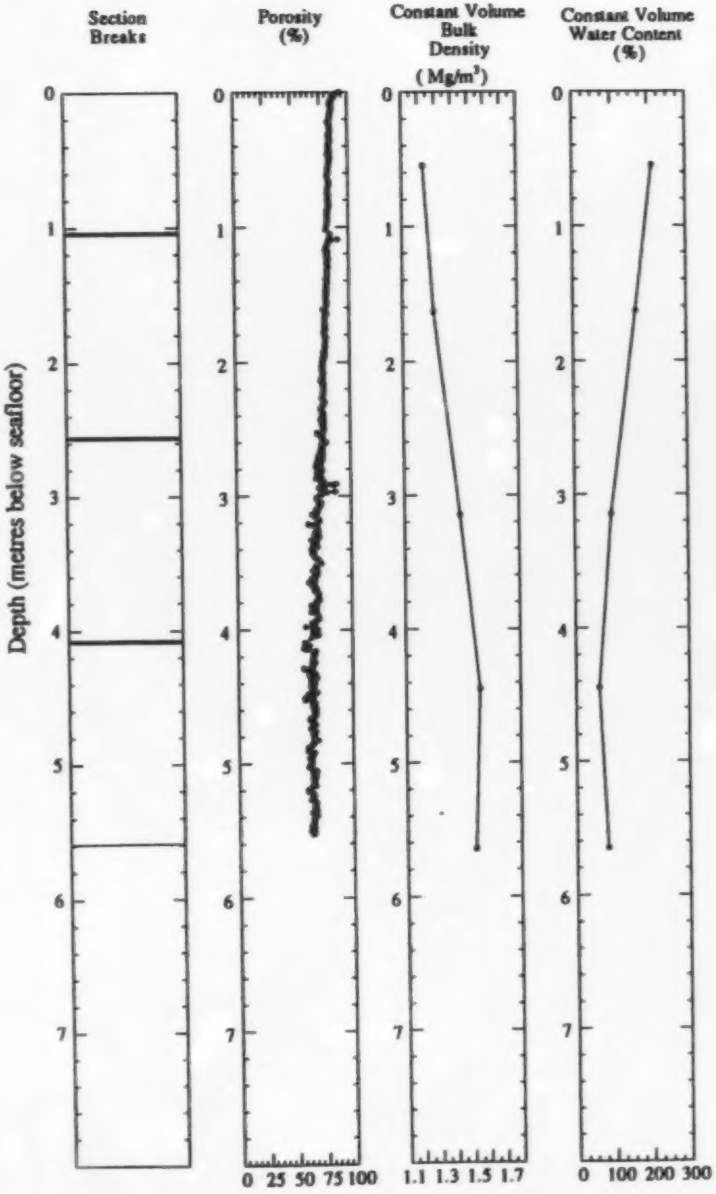
96900 Lake Winnipeg 204 gravity core



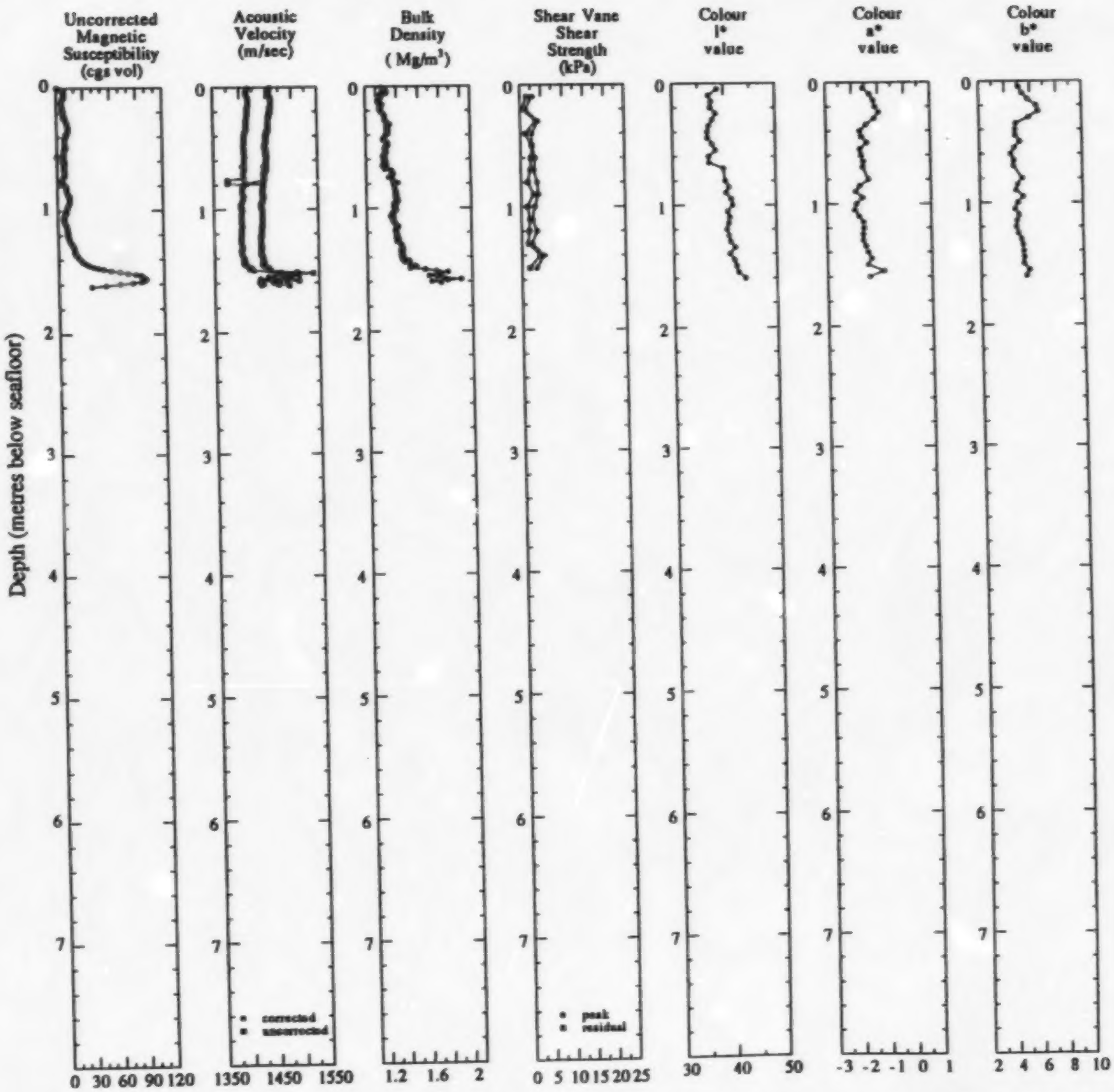
96900 Lake Winnipeg 204 piston core



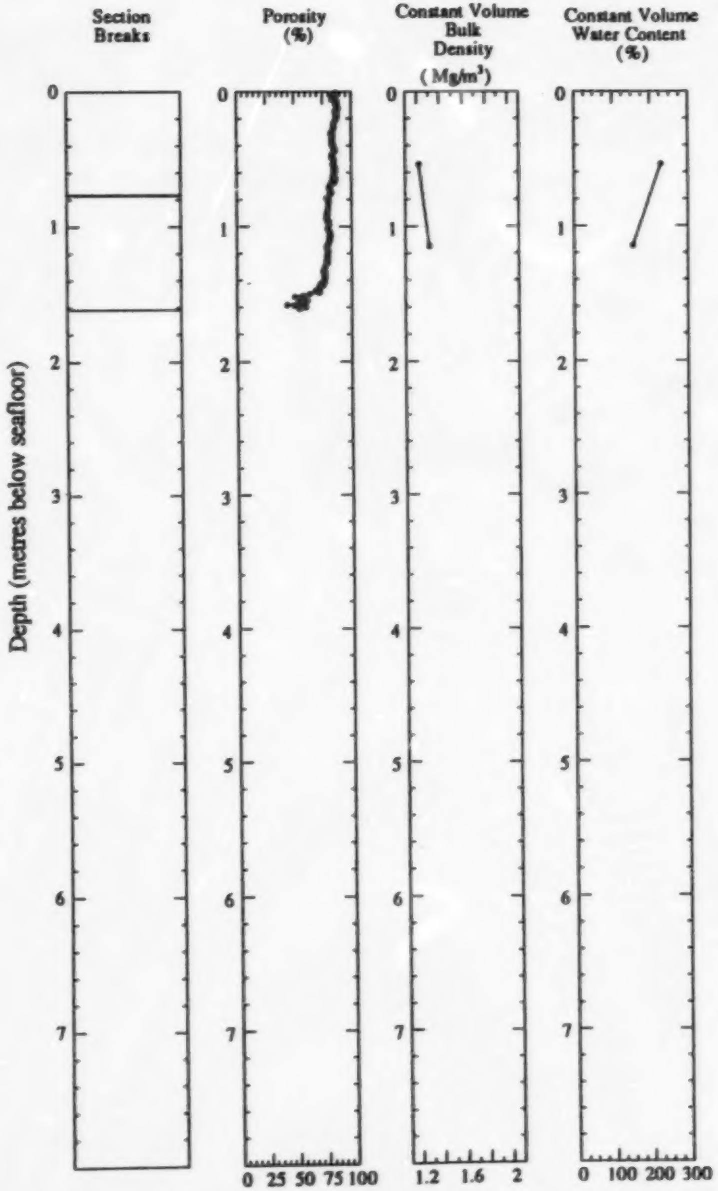
96900 Lake Winnipeg 204 piston core



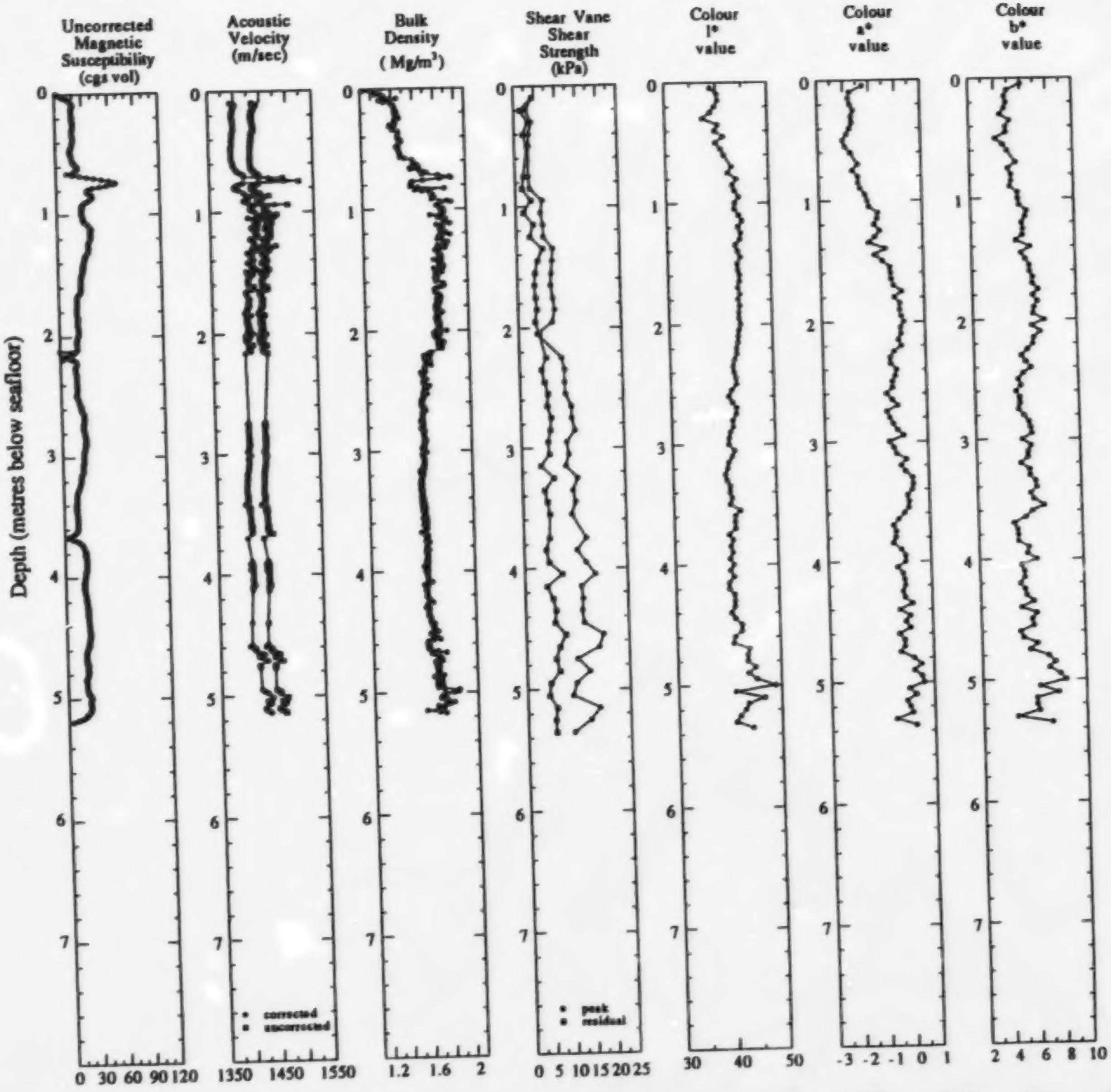
96900 Lake Winnipeg 205 gravity core



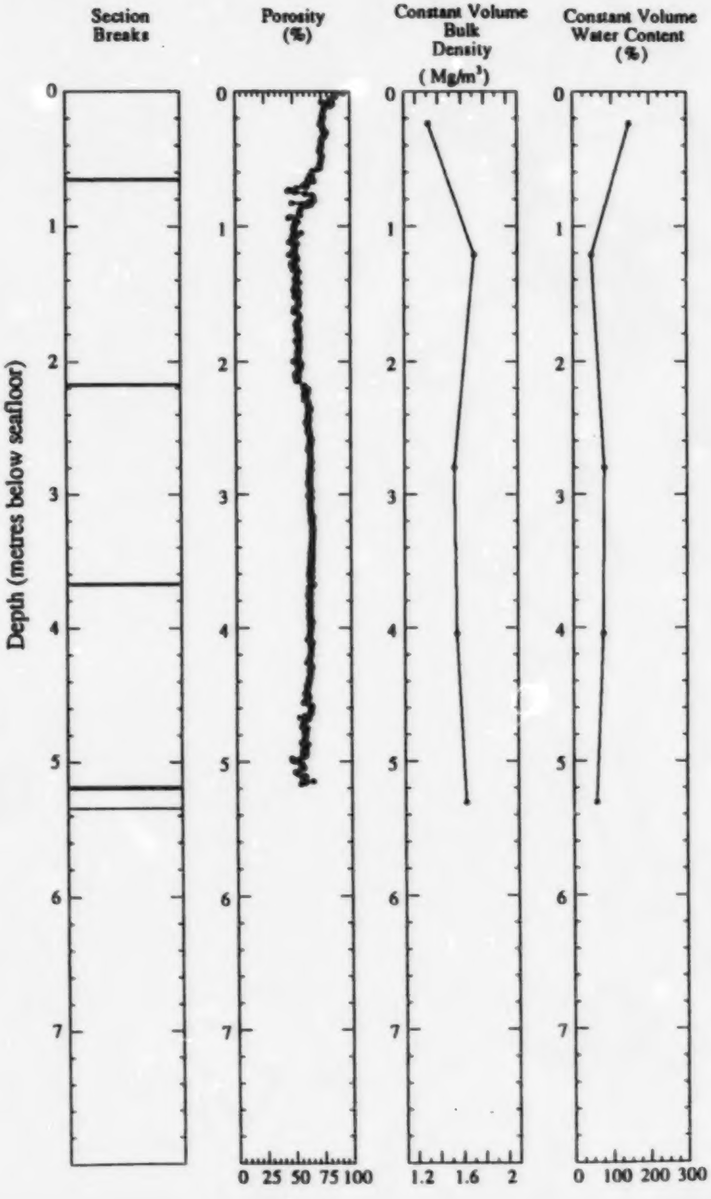
96900 Lake Winnipeg 205 gravity core



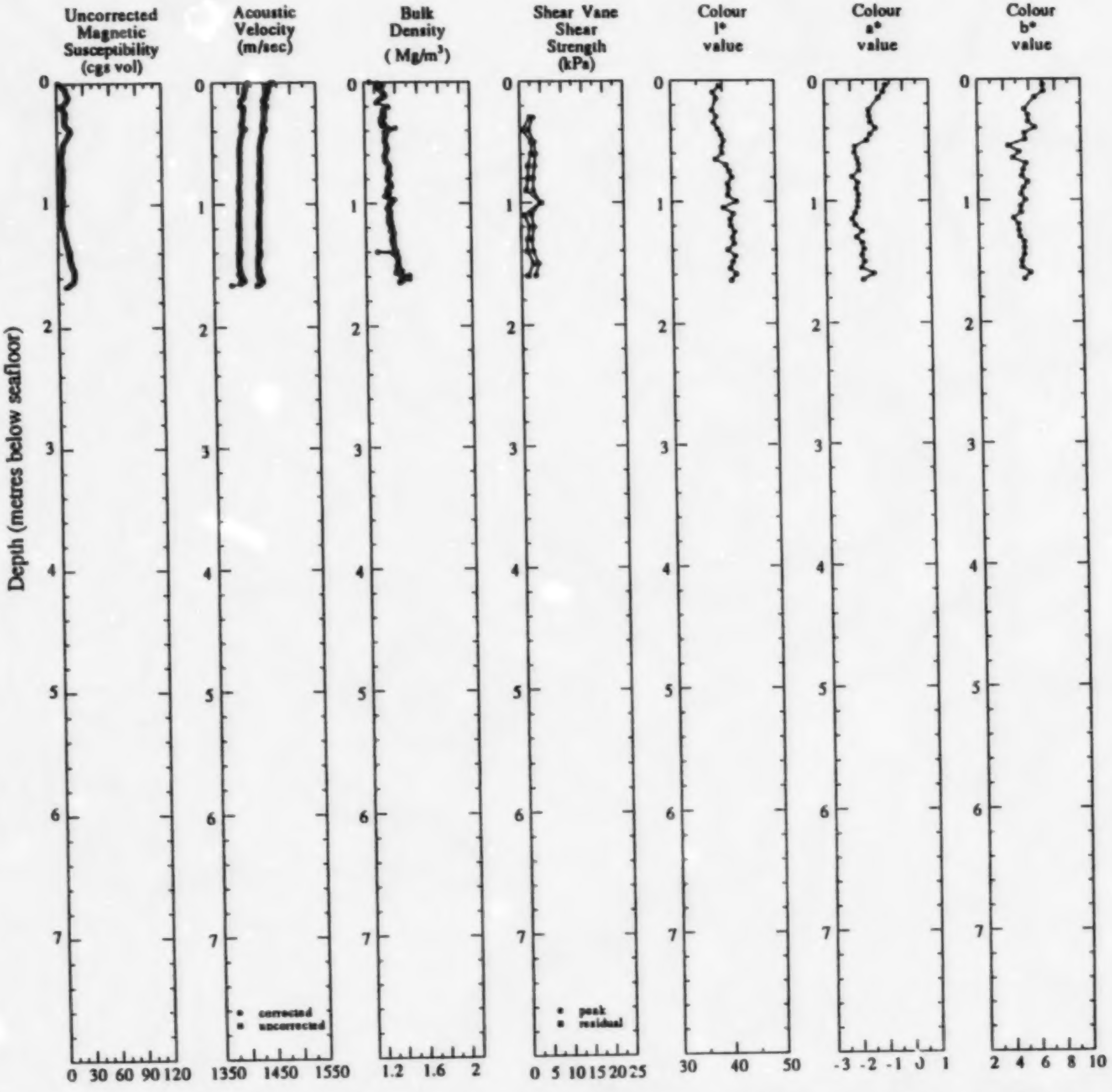
96900 Lake Winnipeg 205 piston core



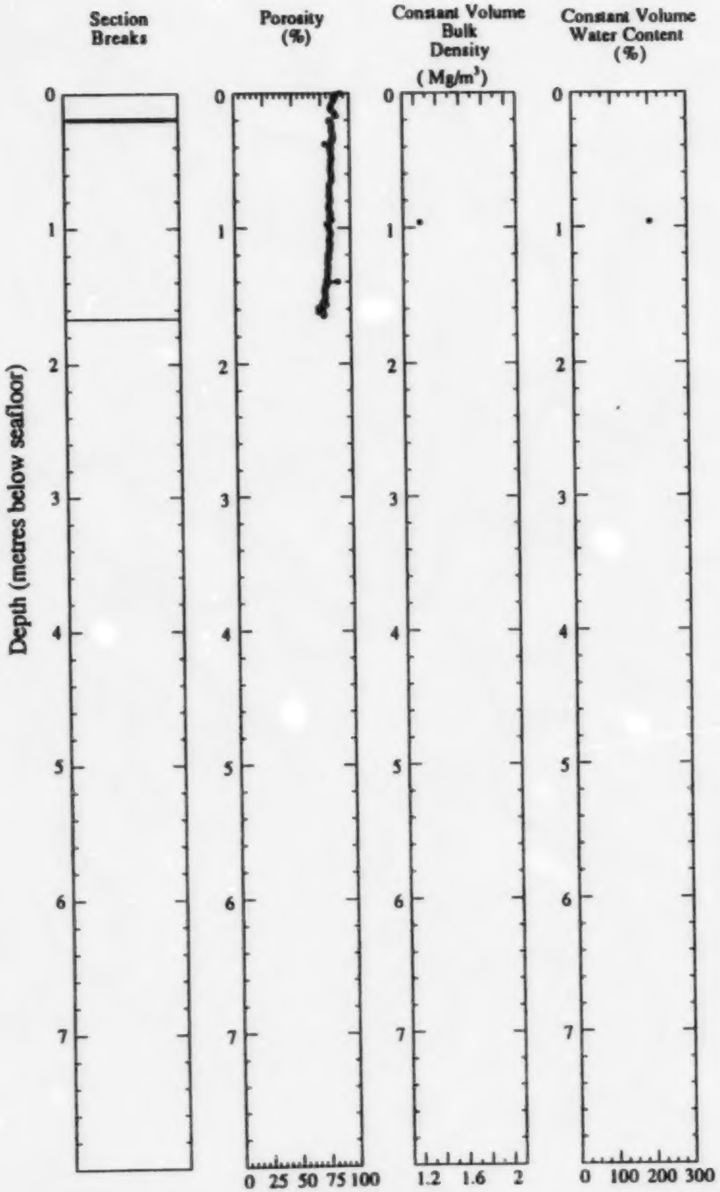
96900 Lake Winnipeg 205 piston core



96900 Lake Winnipeg 206 gravity core



96900 Lake Winnipeg 206 gravity core



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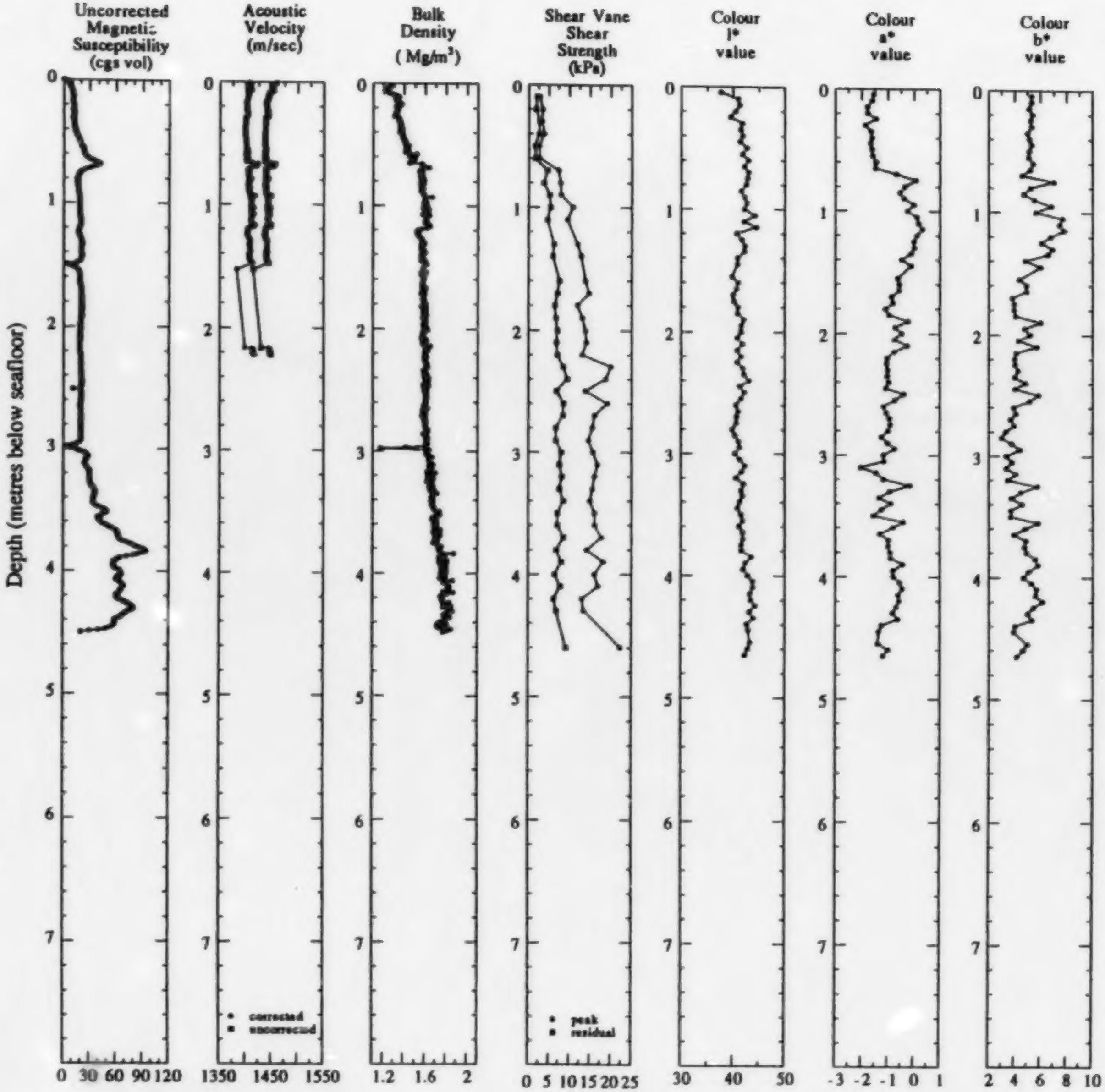
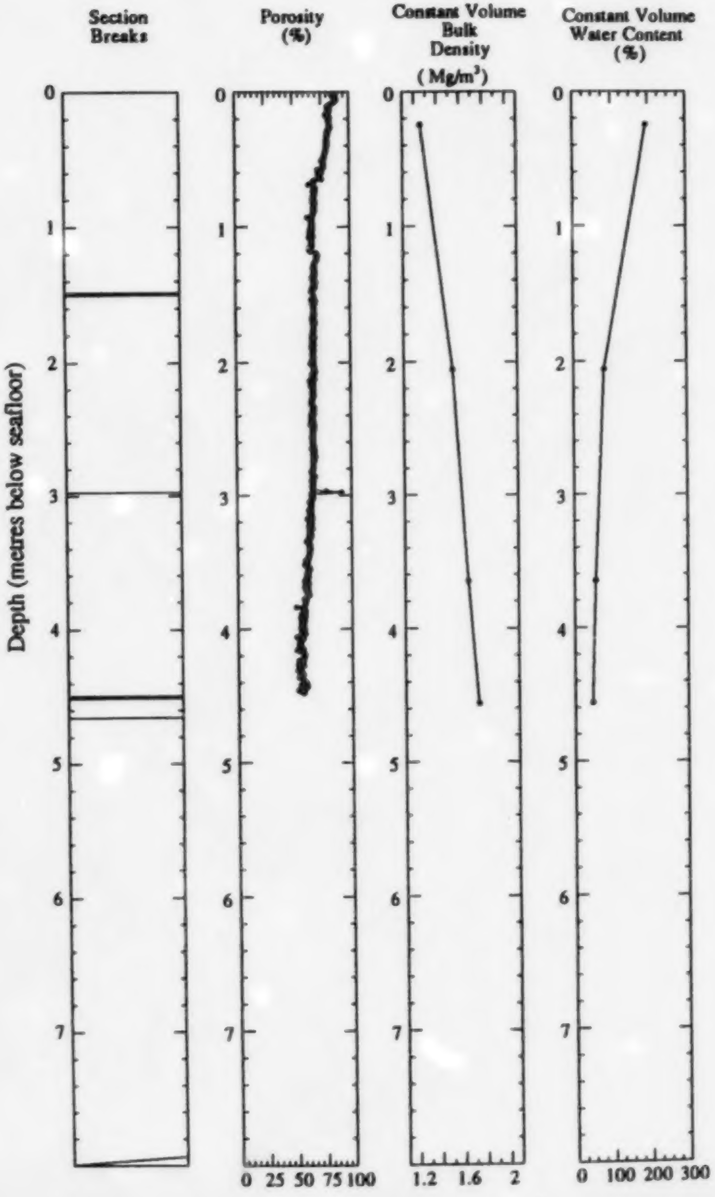
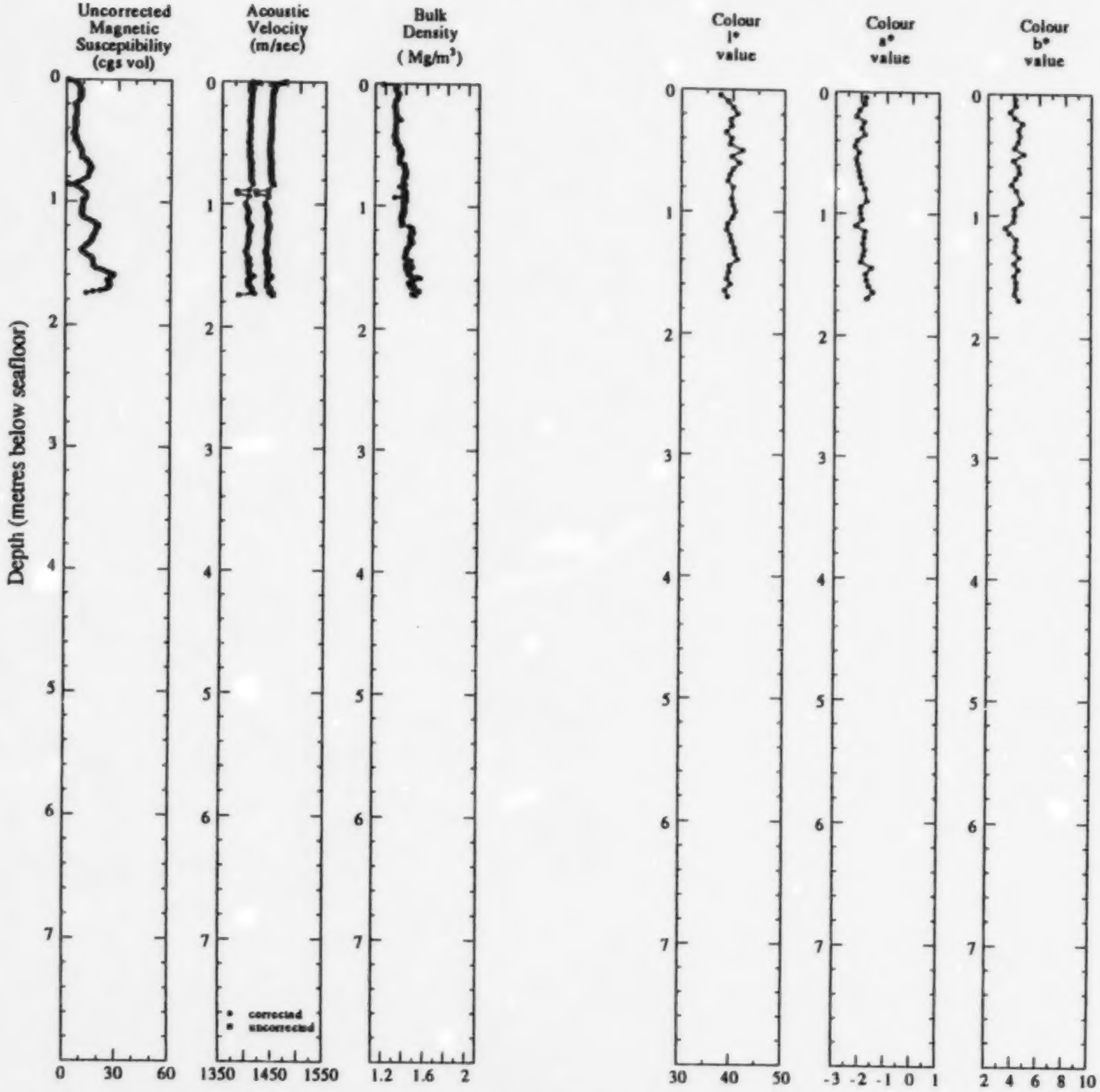


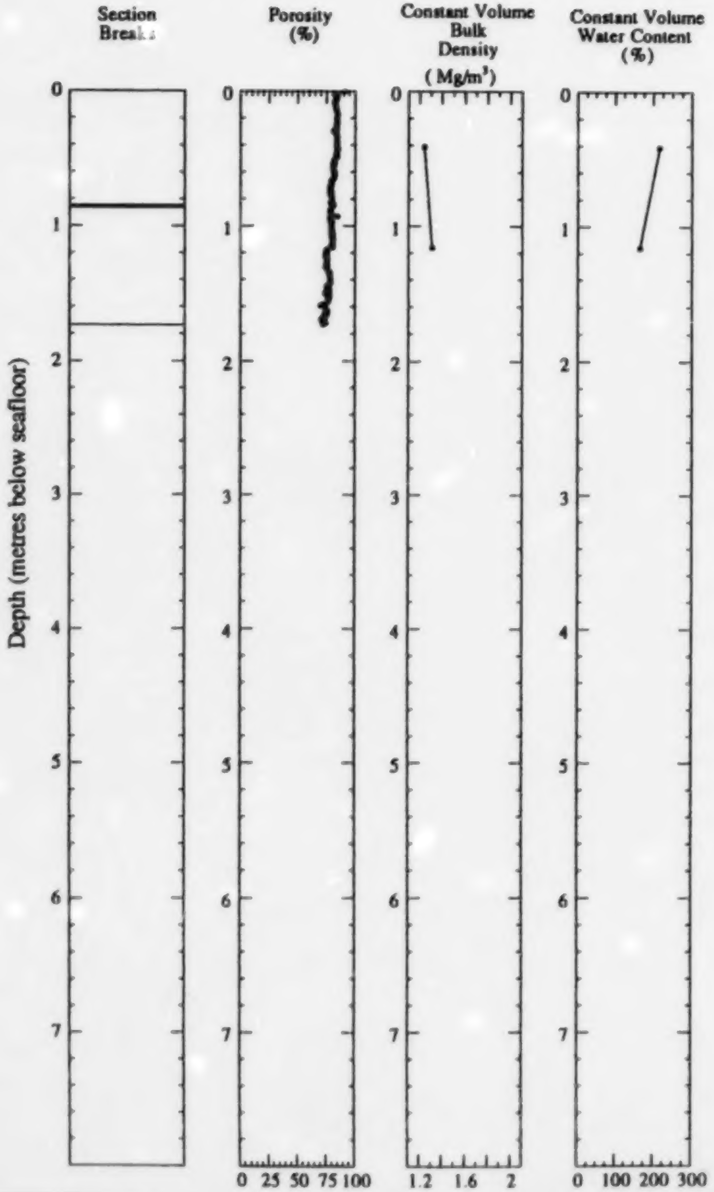
96900 Lake Winnipeg 206 piston core



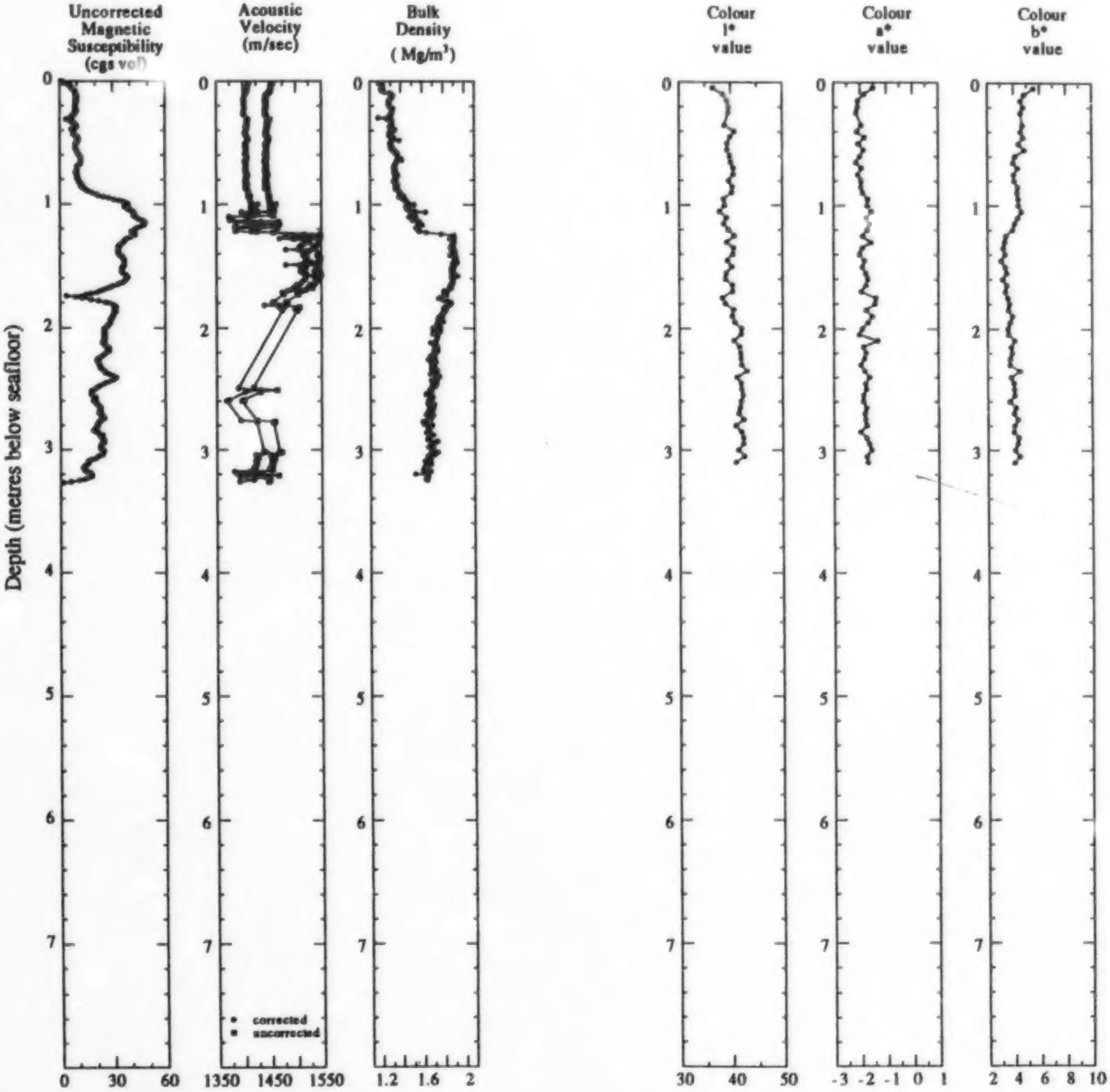
96900 Lake Winnipeg 207 gravity core



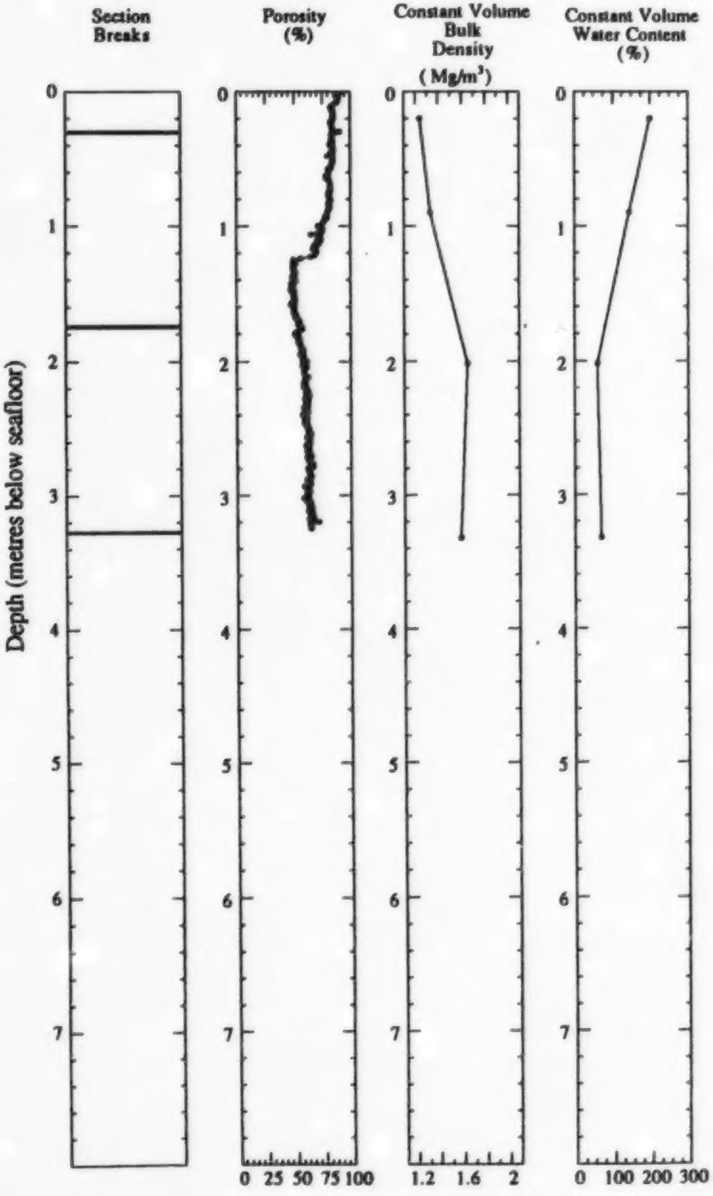
96900 Lake Winnipeg 207 gravity core



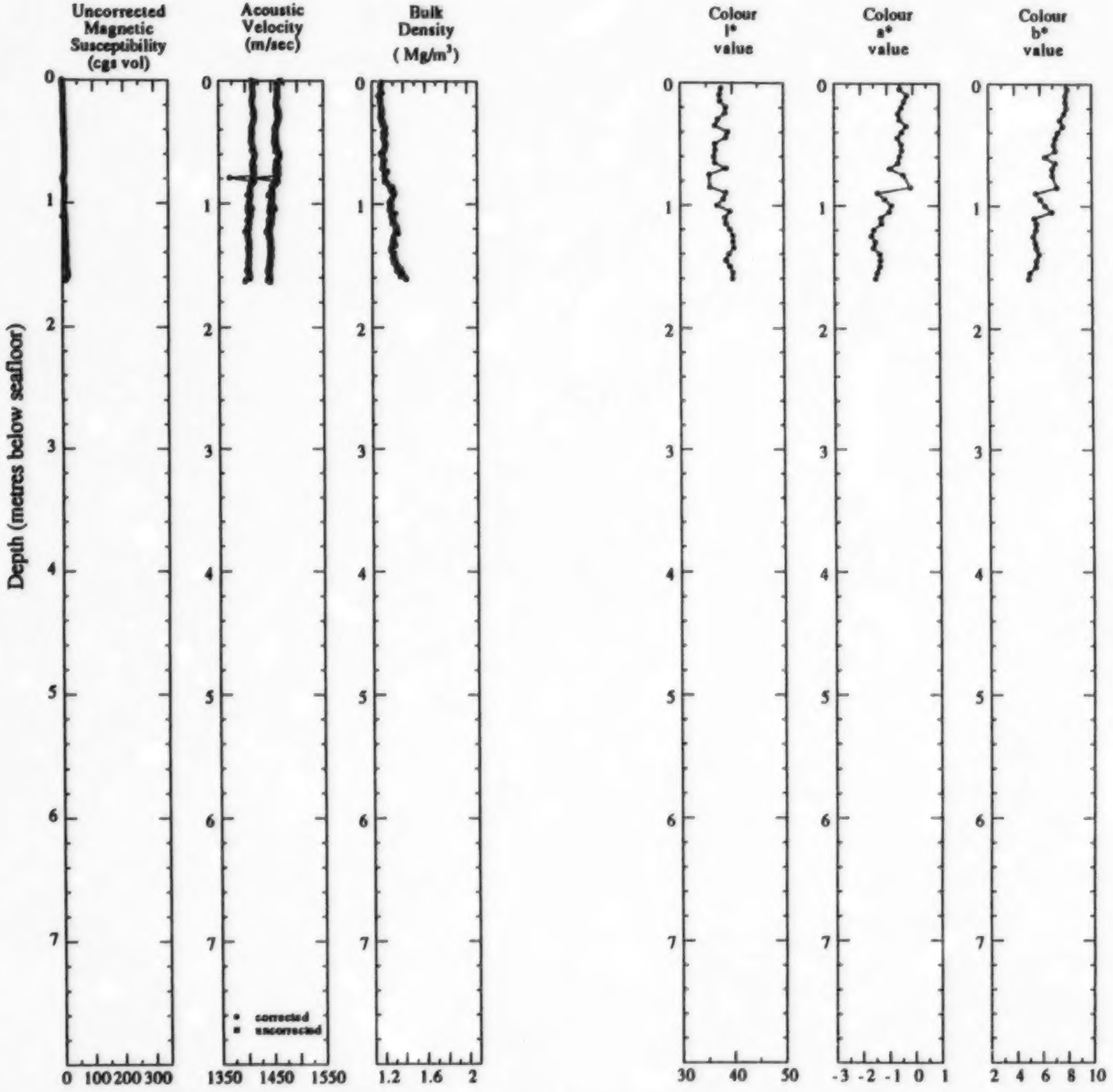
96900 Lake Winnipeg 207 piston core



96900 Lake Winnipeg 207 piston core



96900 Lake Winnipeg 208 gravity core



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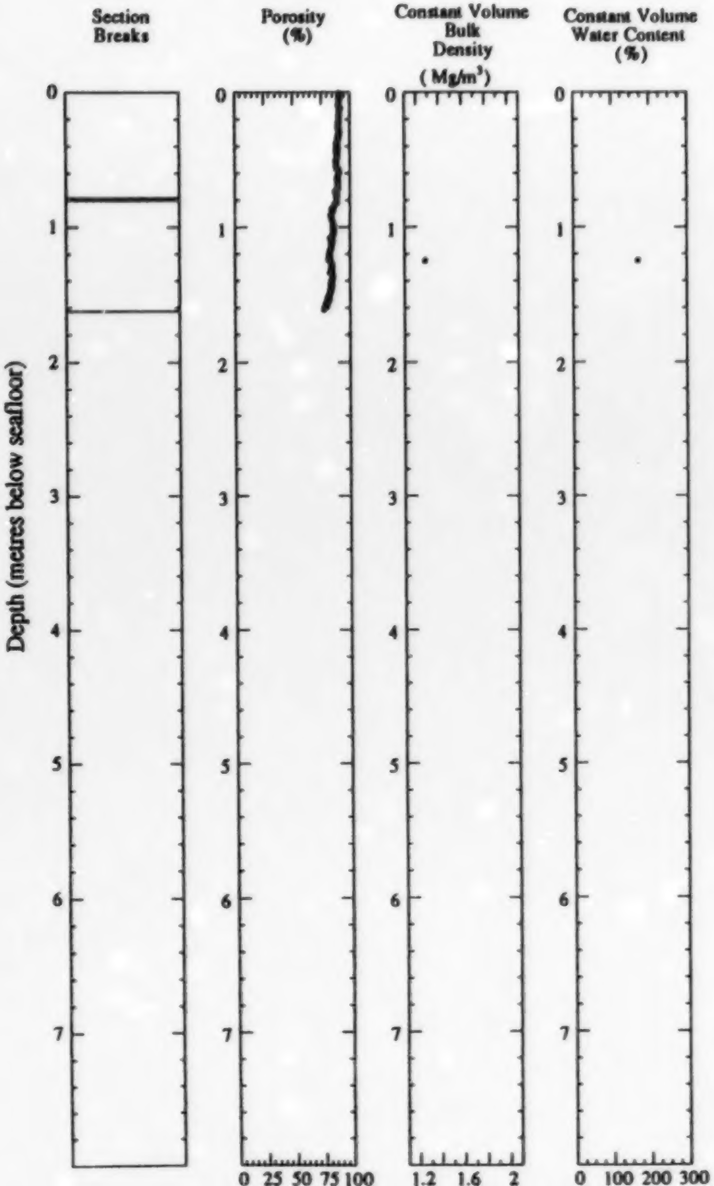
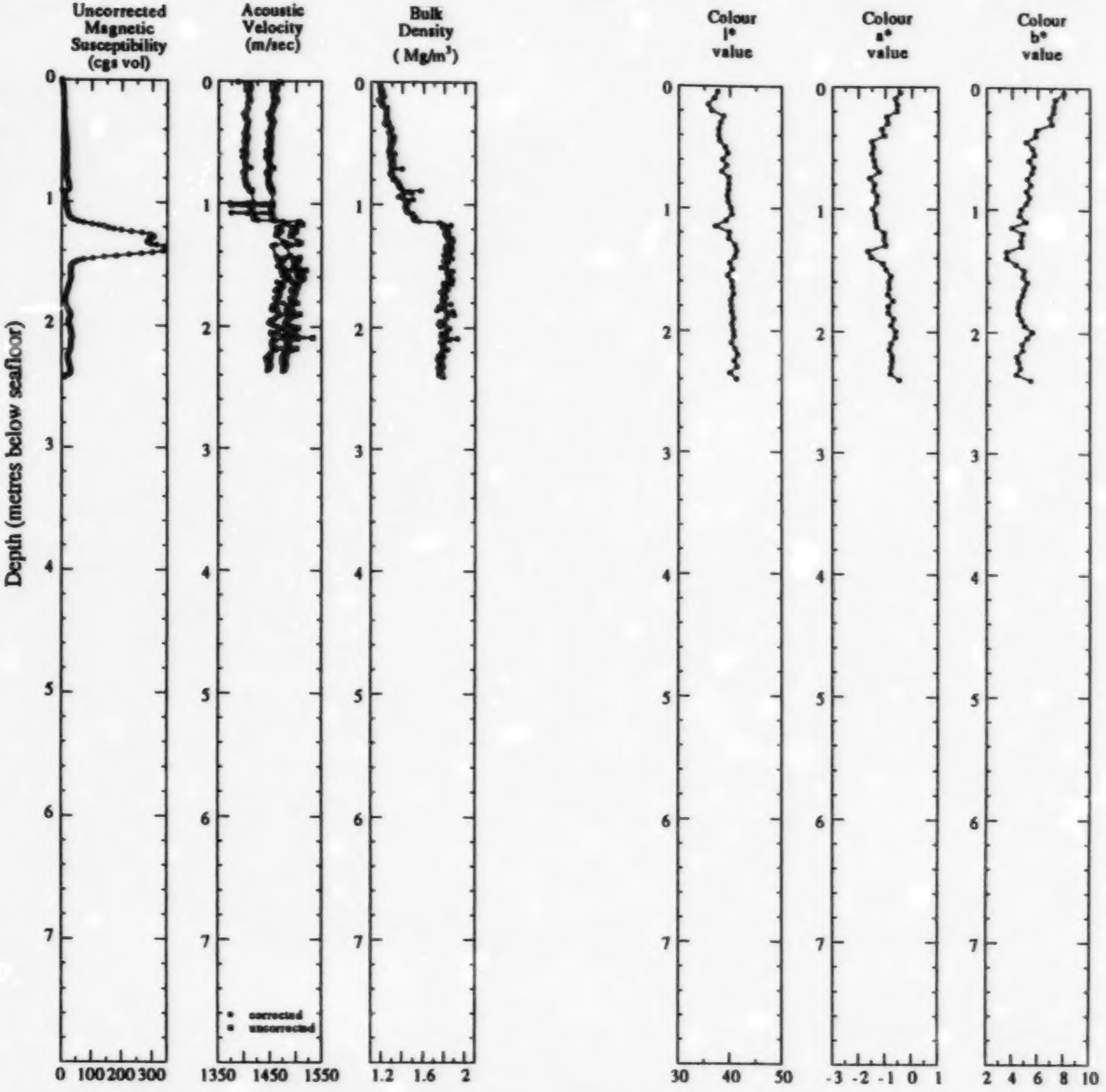


96900 Lake Winnipeg 208 piston core



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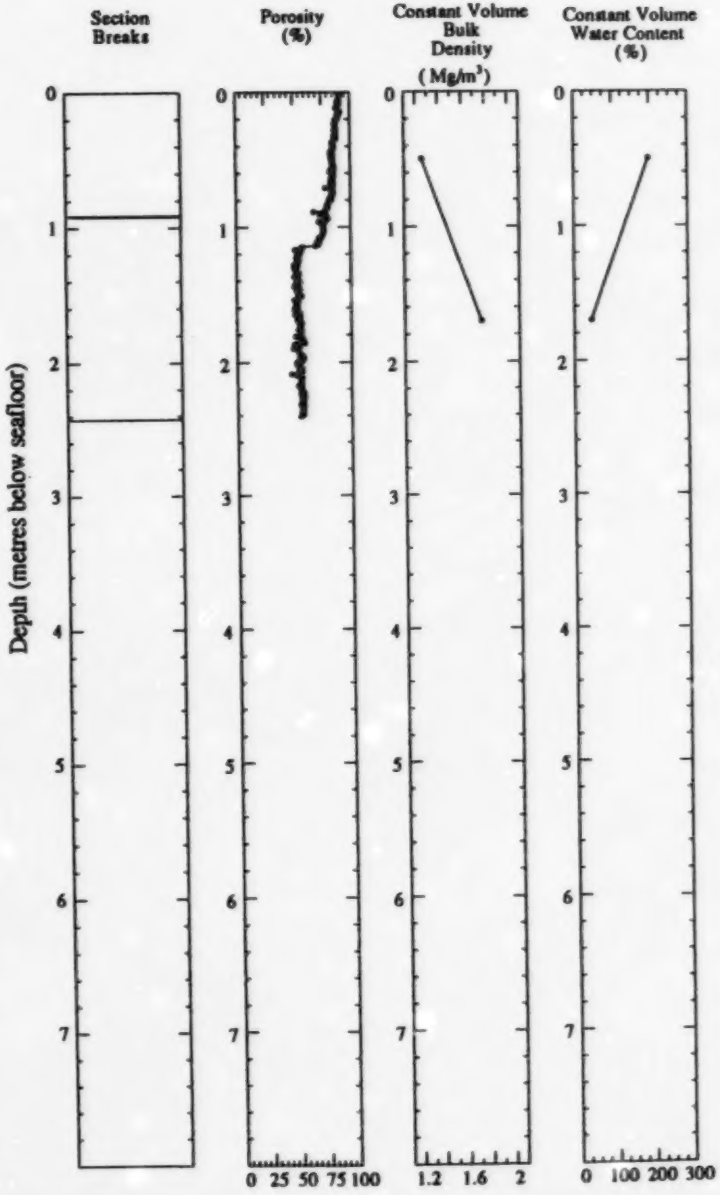
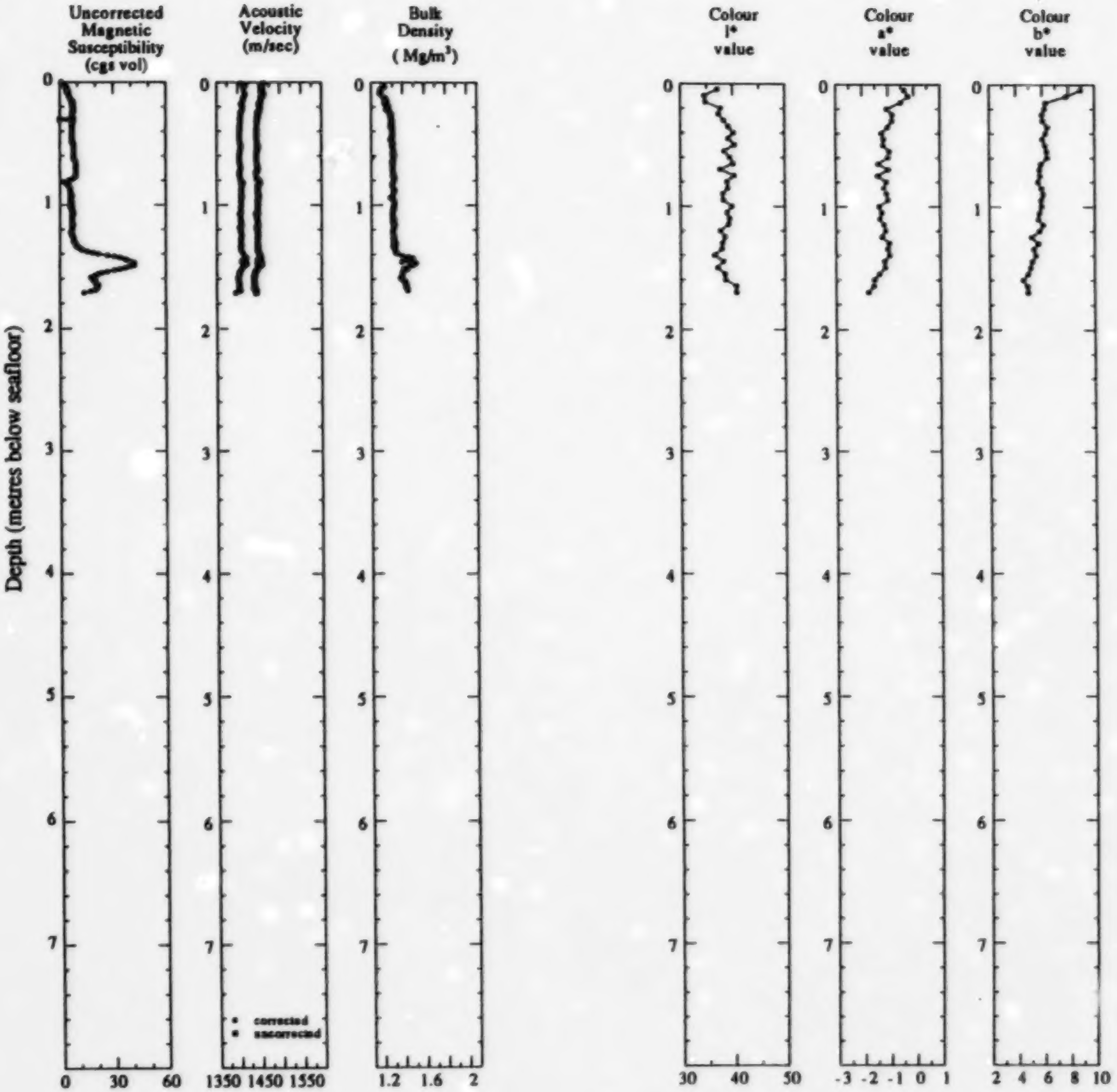
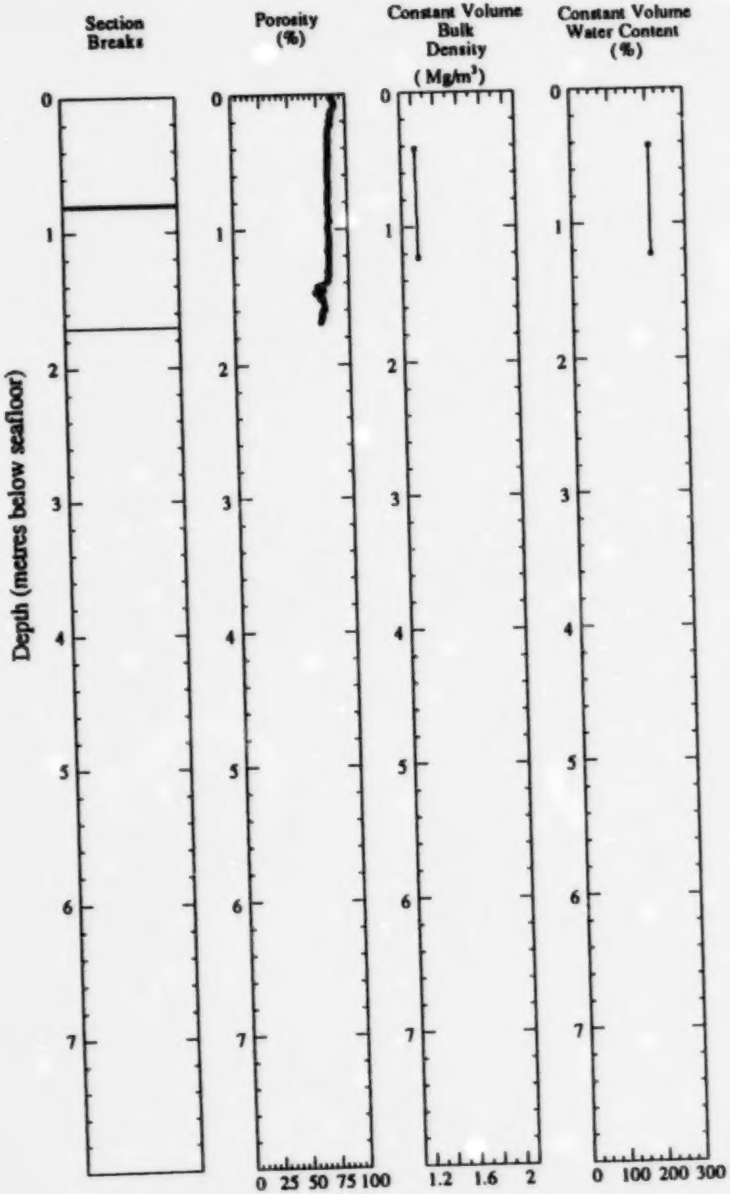


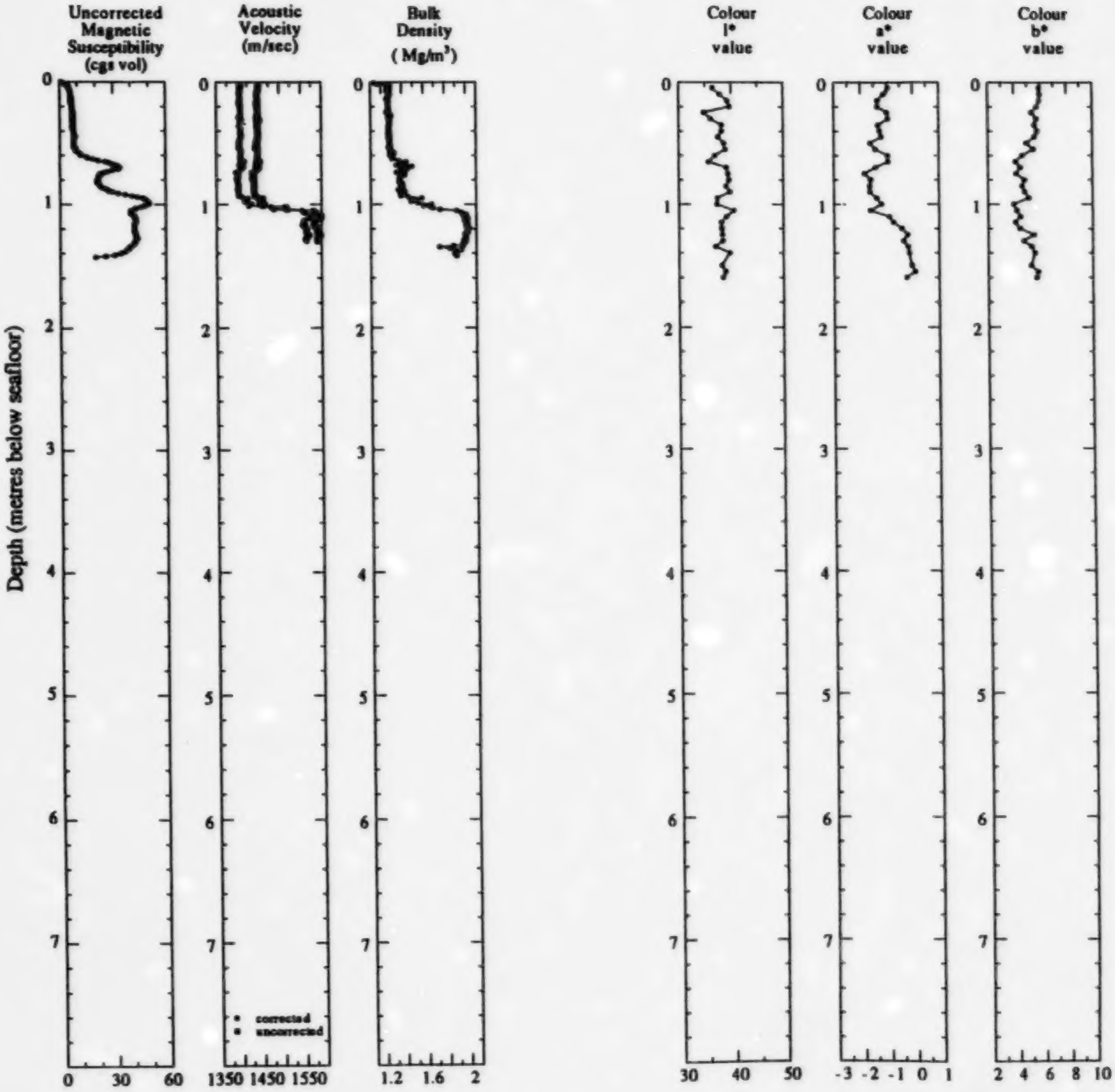
96900 Lake Winnipeg 209 gravity core



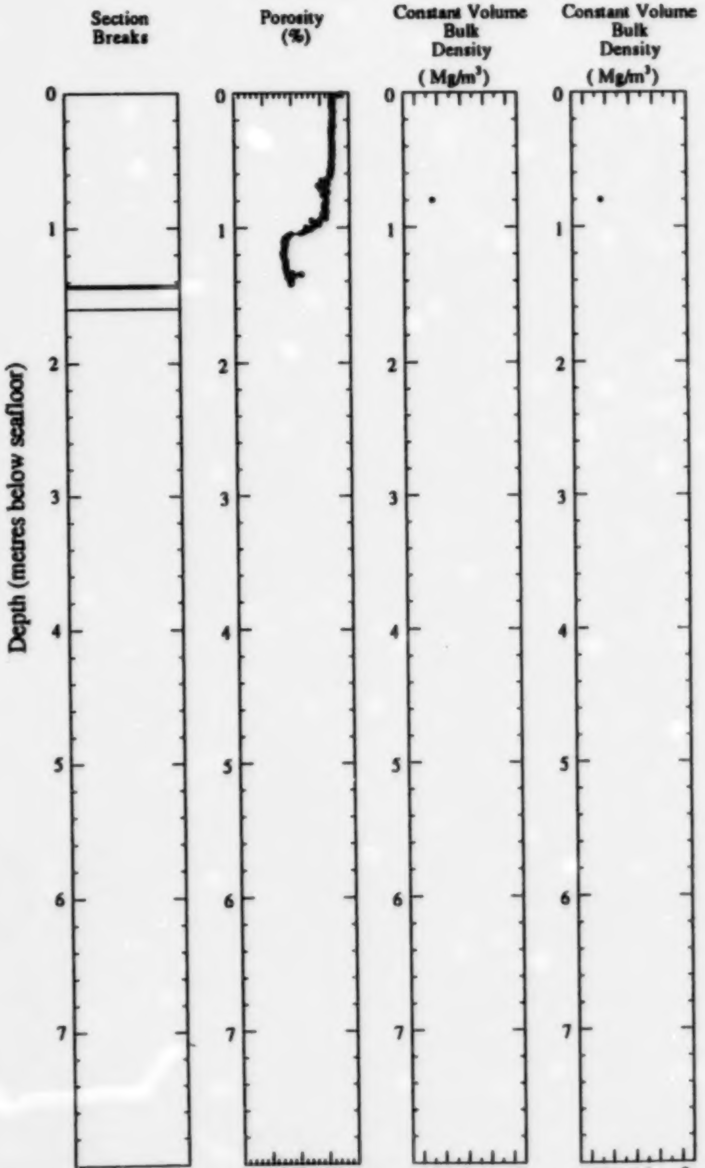
96900 Lake Winnipeg 209 gravity core



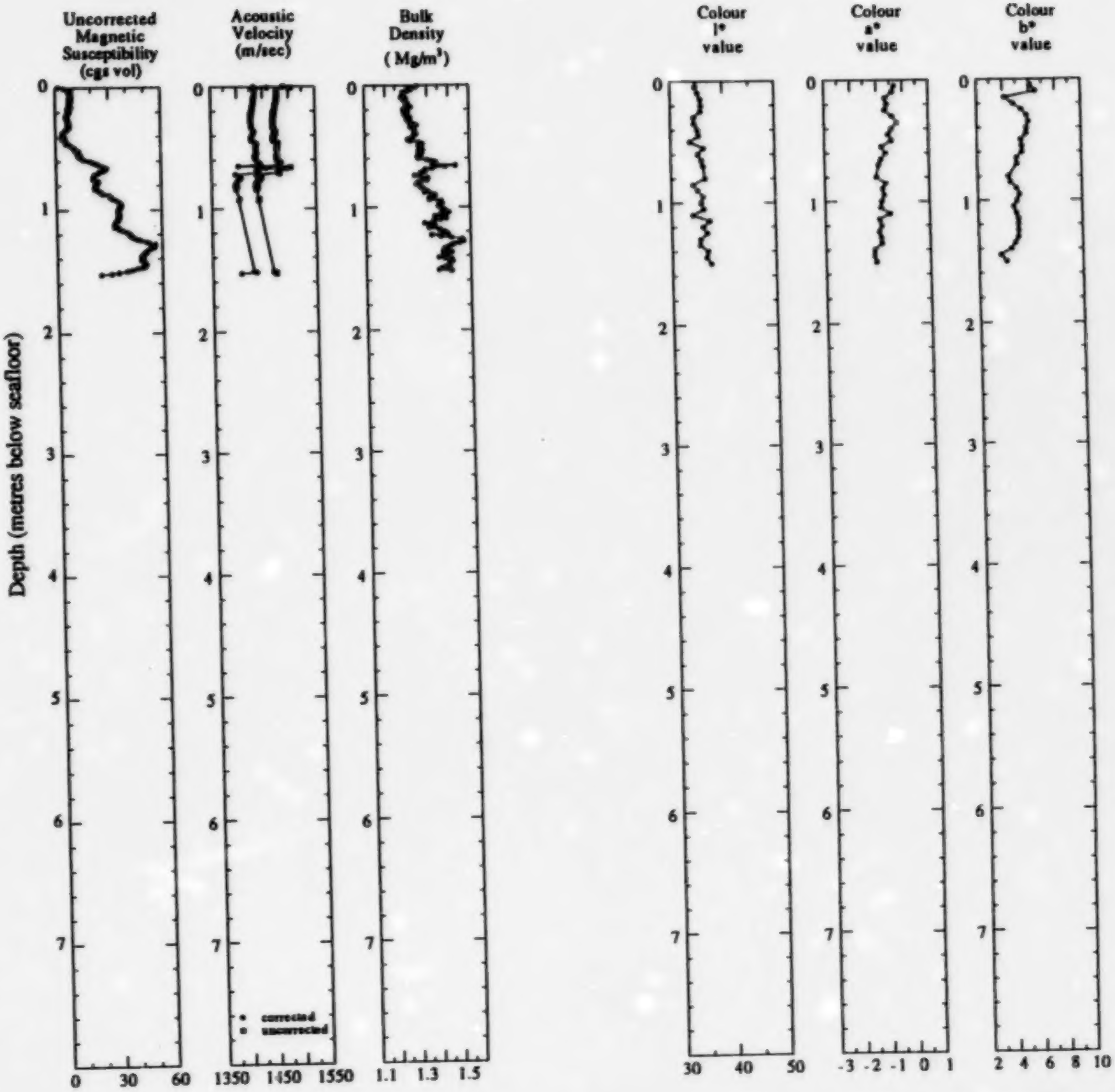
96900 Lake Winnipeg 209 piston core



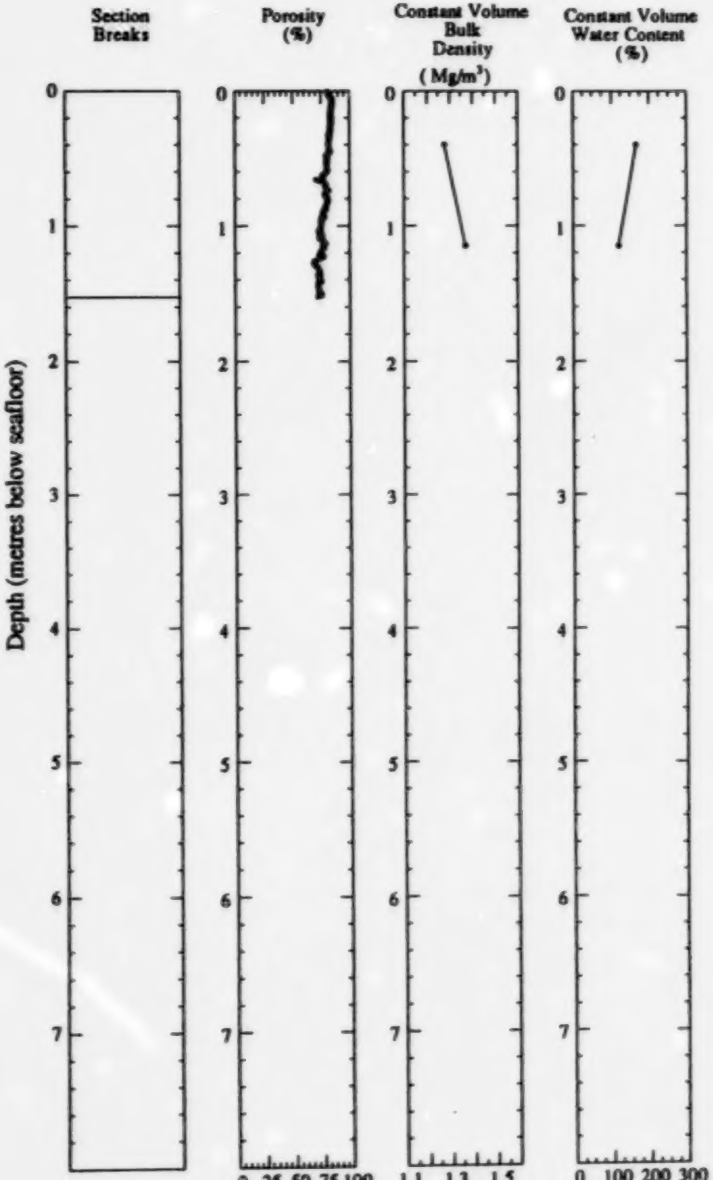
96900 Lake Winnipeg 209 piston core



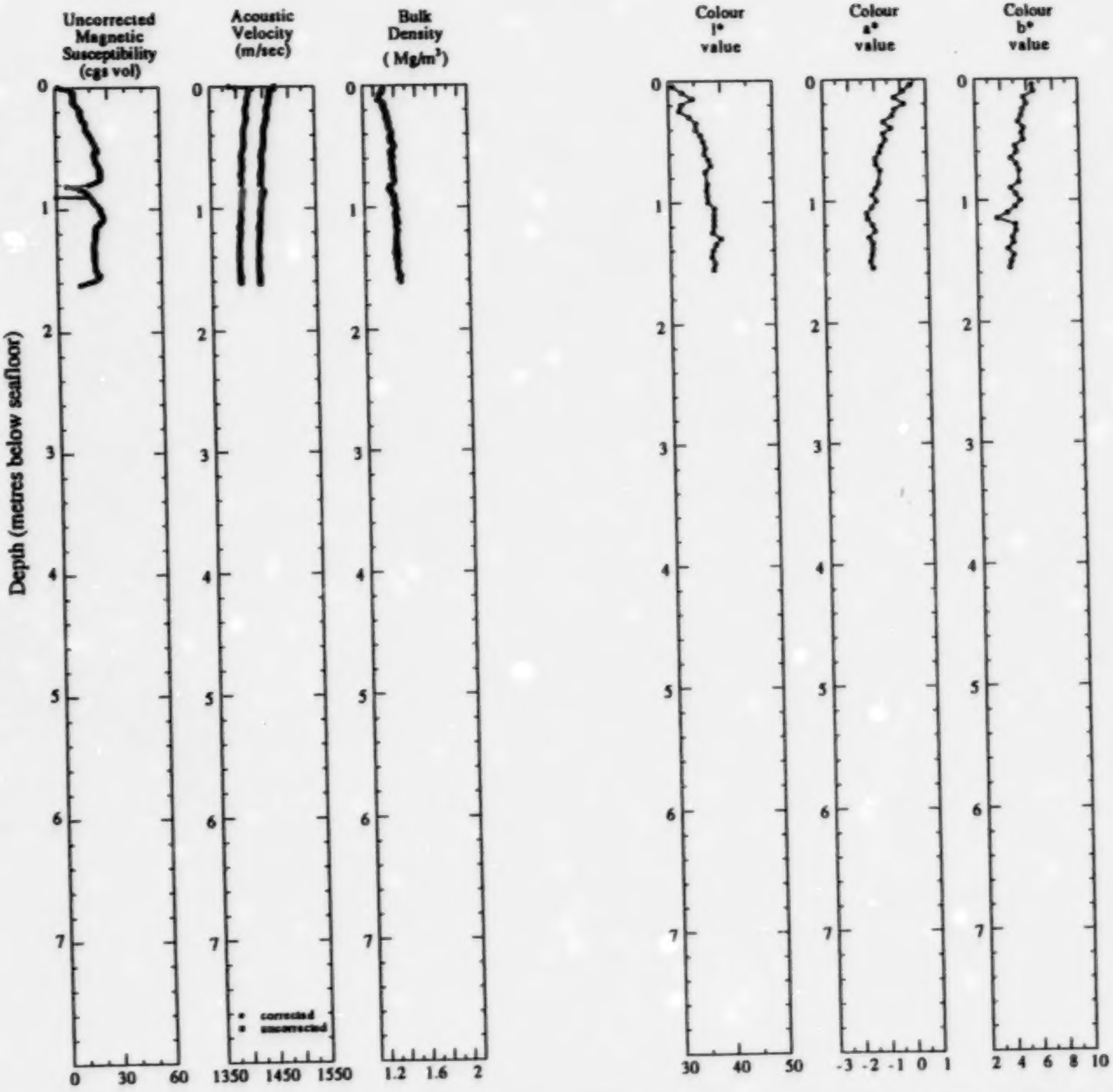
96900 Lake Winnipeg 212 gravity core



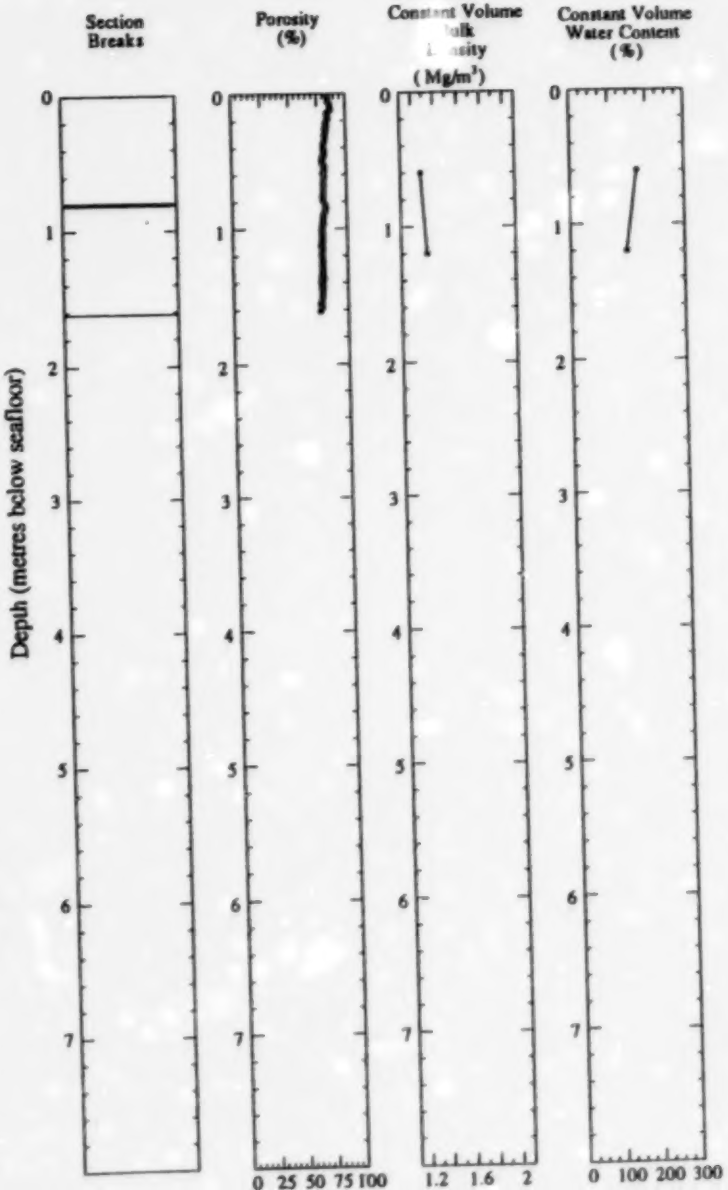
96900 Lake Winnipeg 212 gravity core



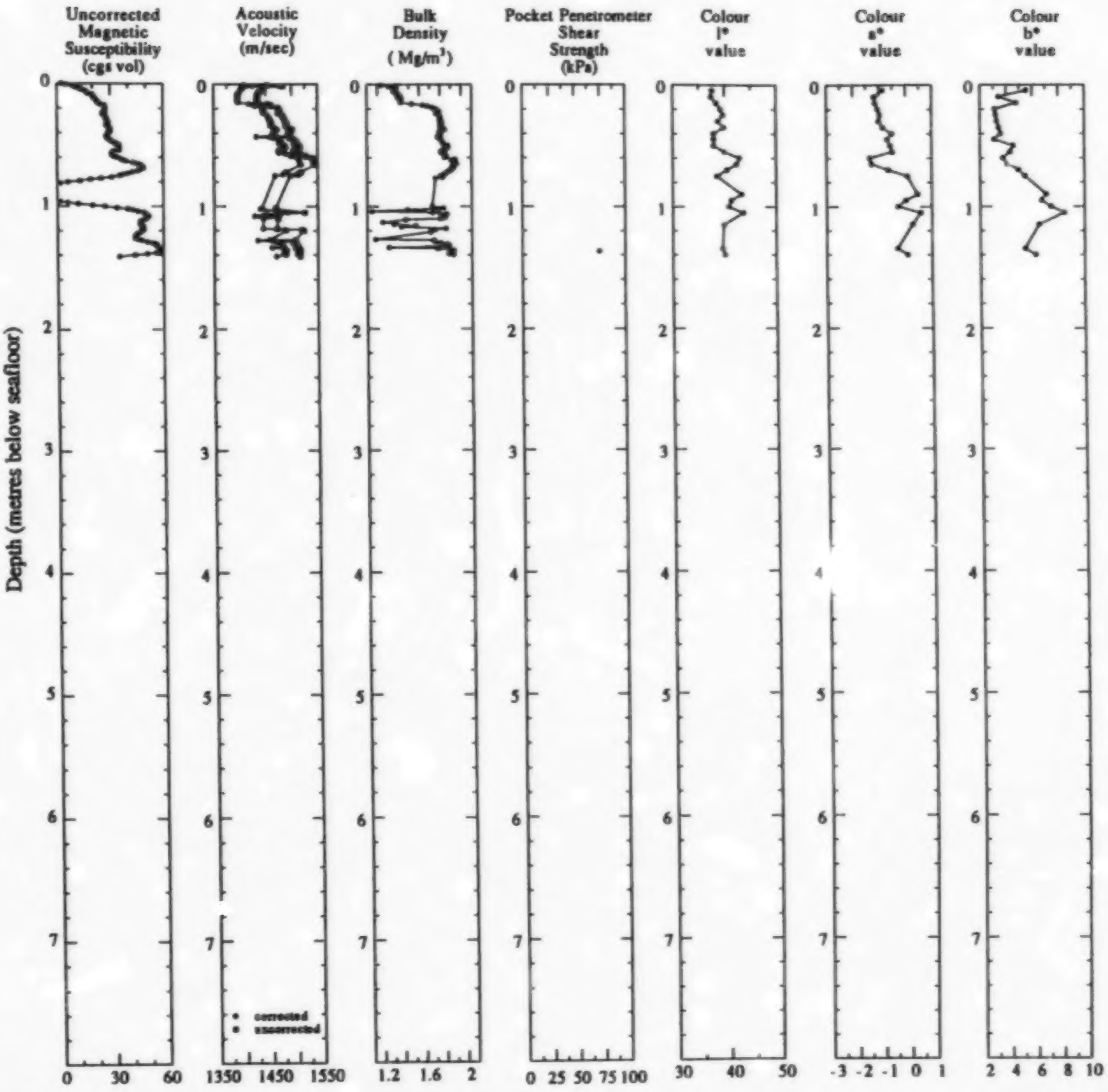
96900 Lake Winnipeg 213 gravity core



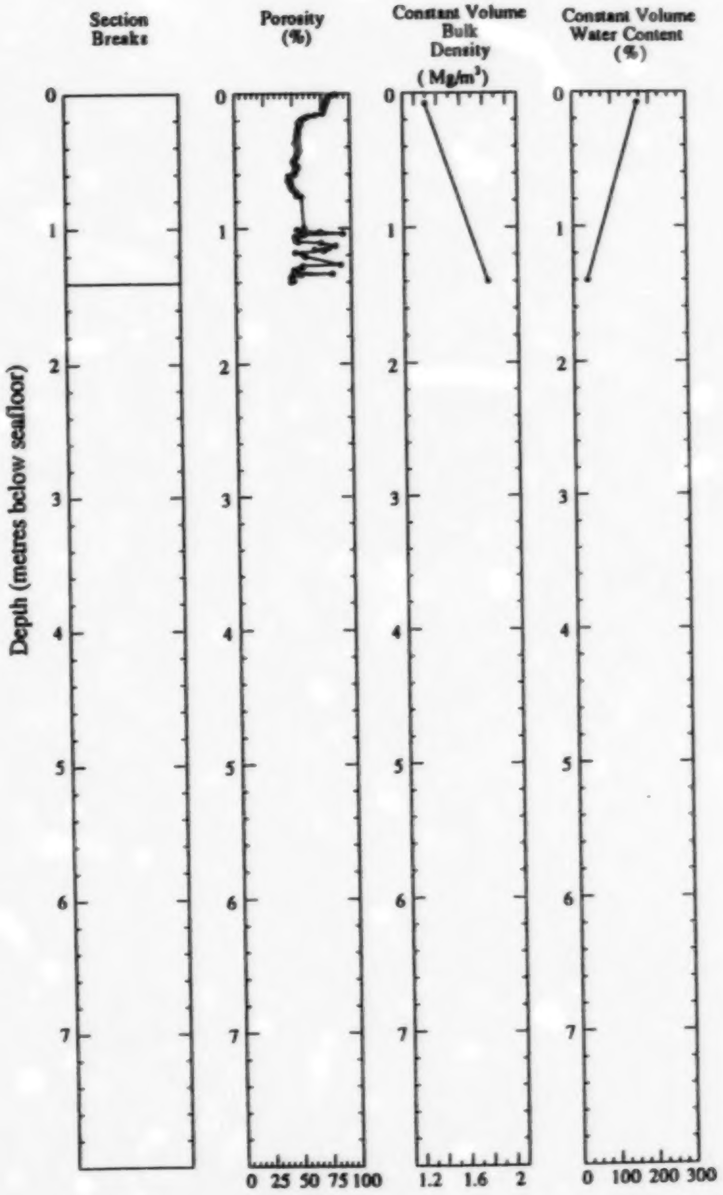
96900 Lake Winnipeg 213 gravity core



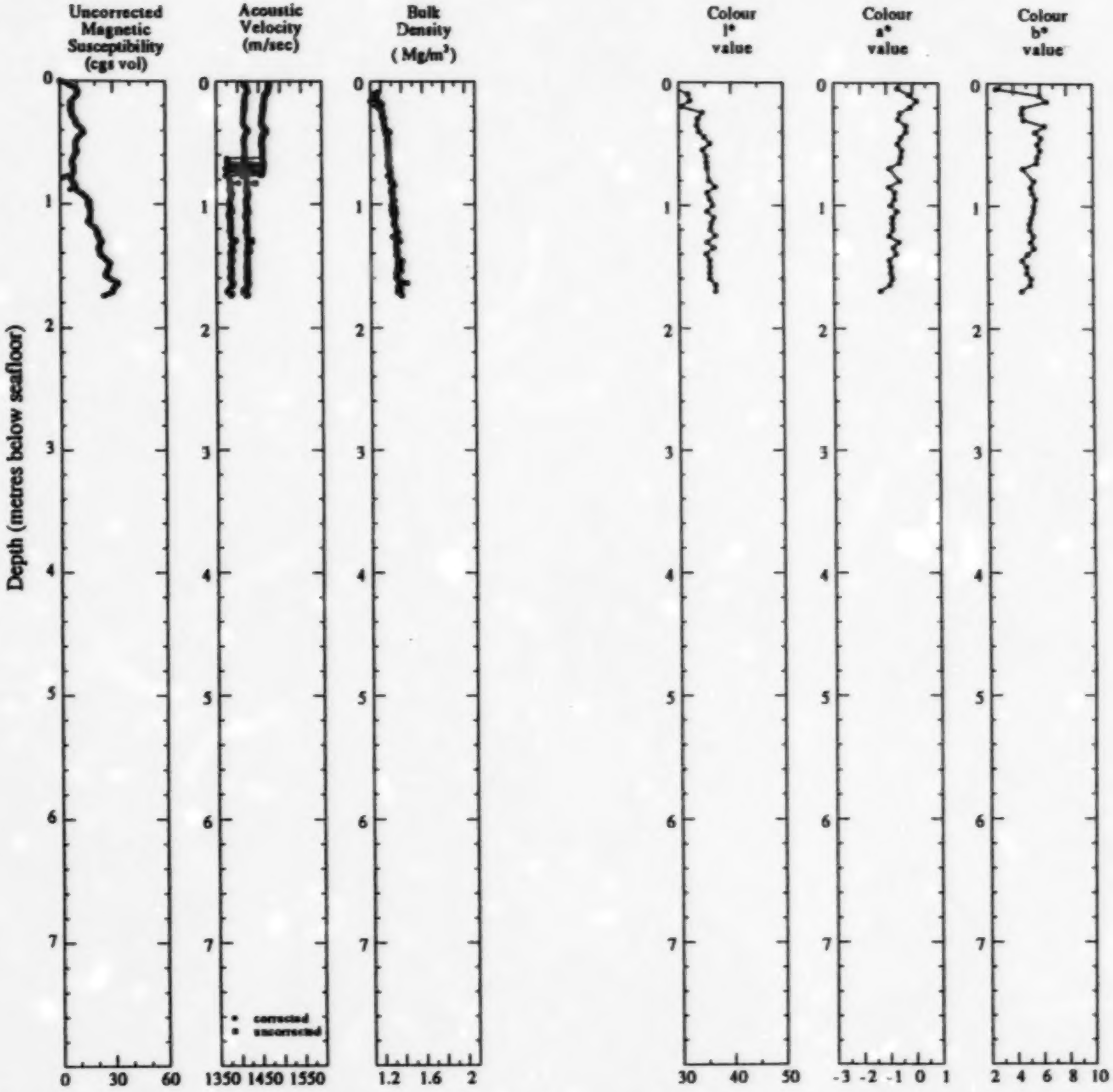
96900 Lake Winnipeg 213 piston core



96900 Lake Winnipeg 213 piston core



96900 Lake Winnipeg 214 gravity core



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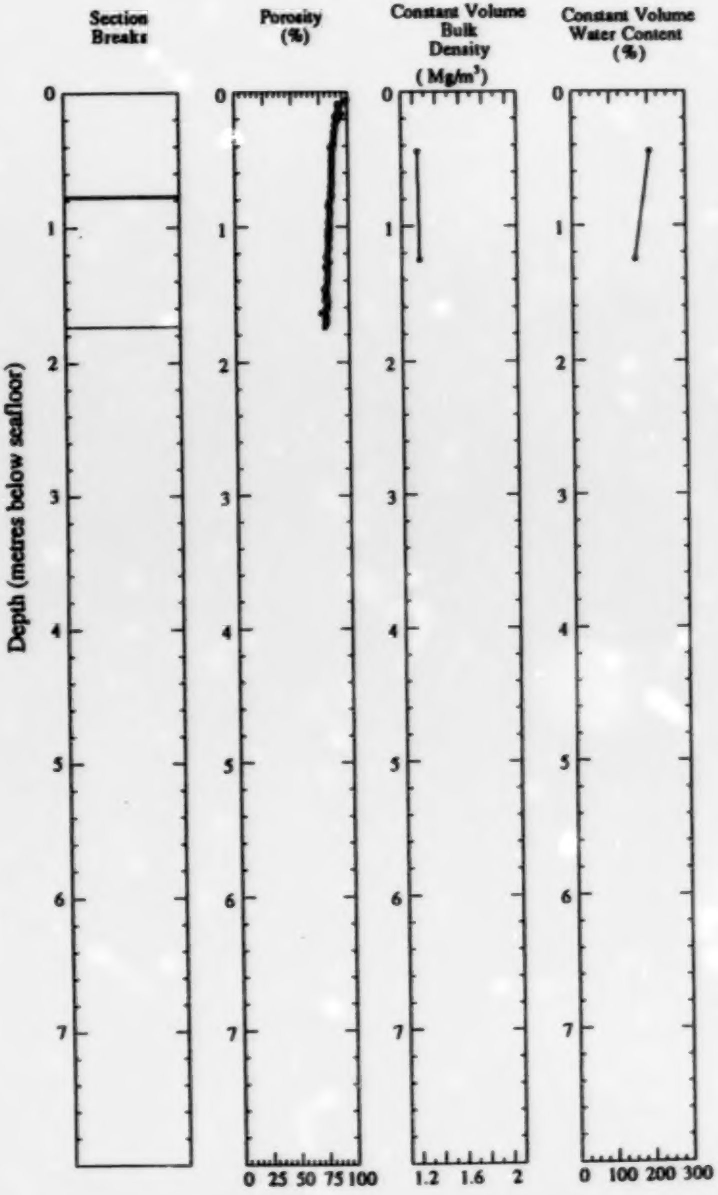

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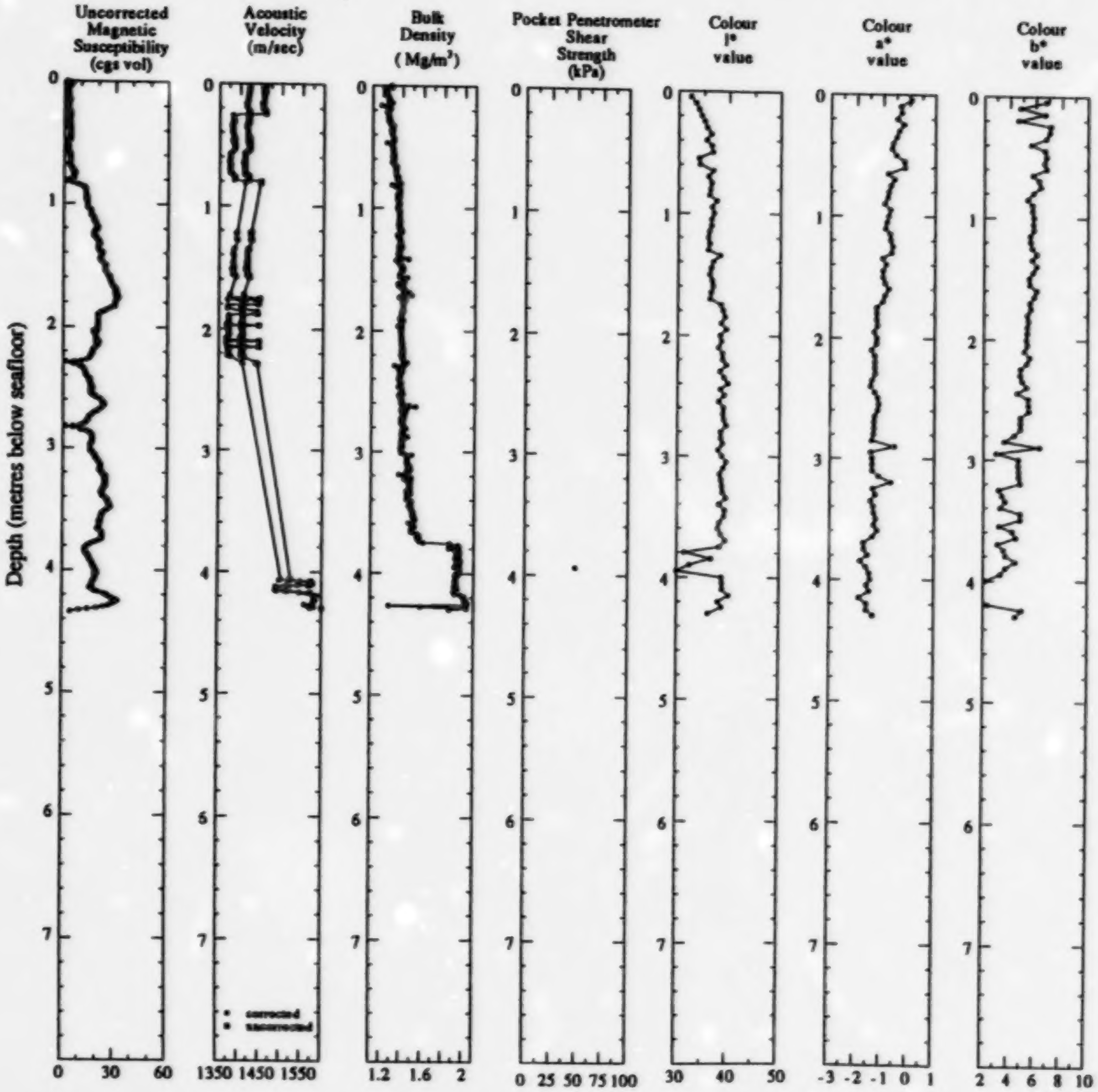

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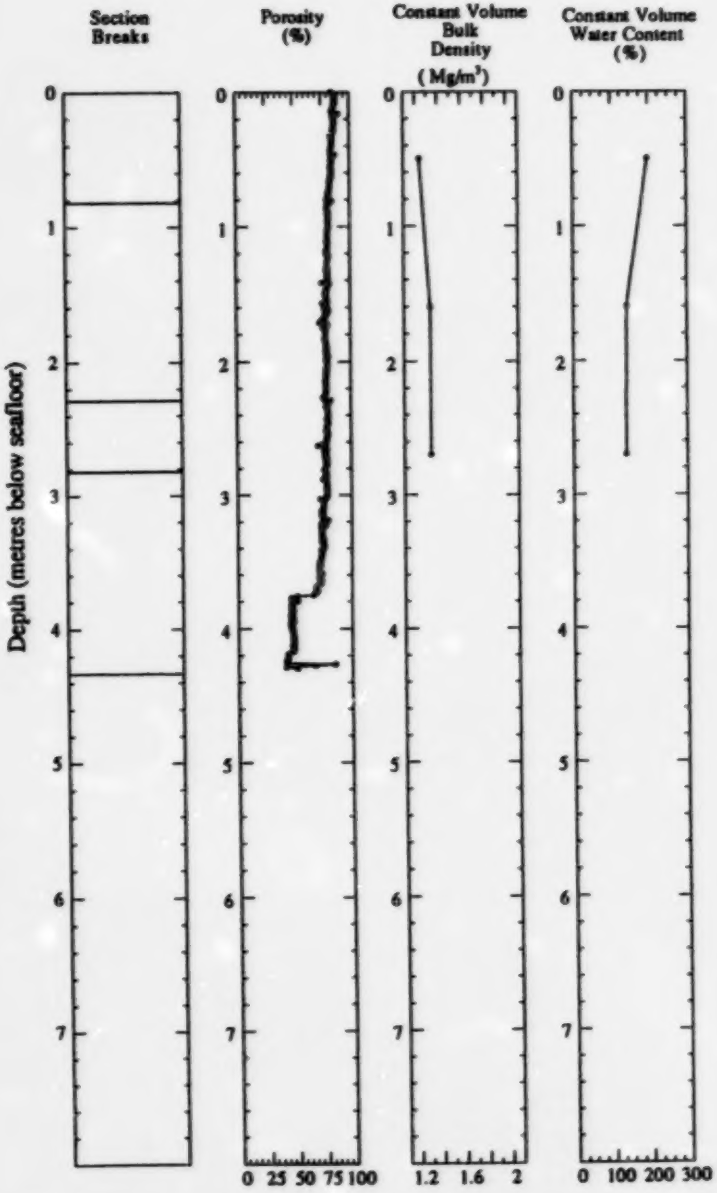

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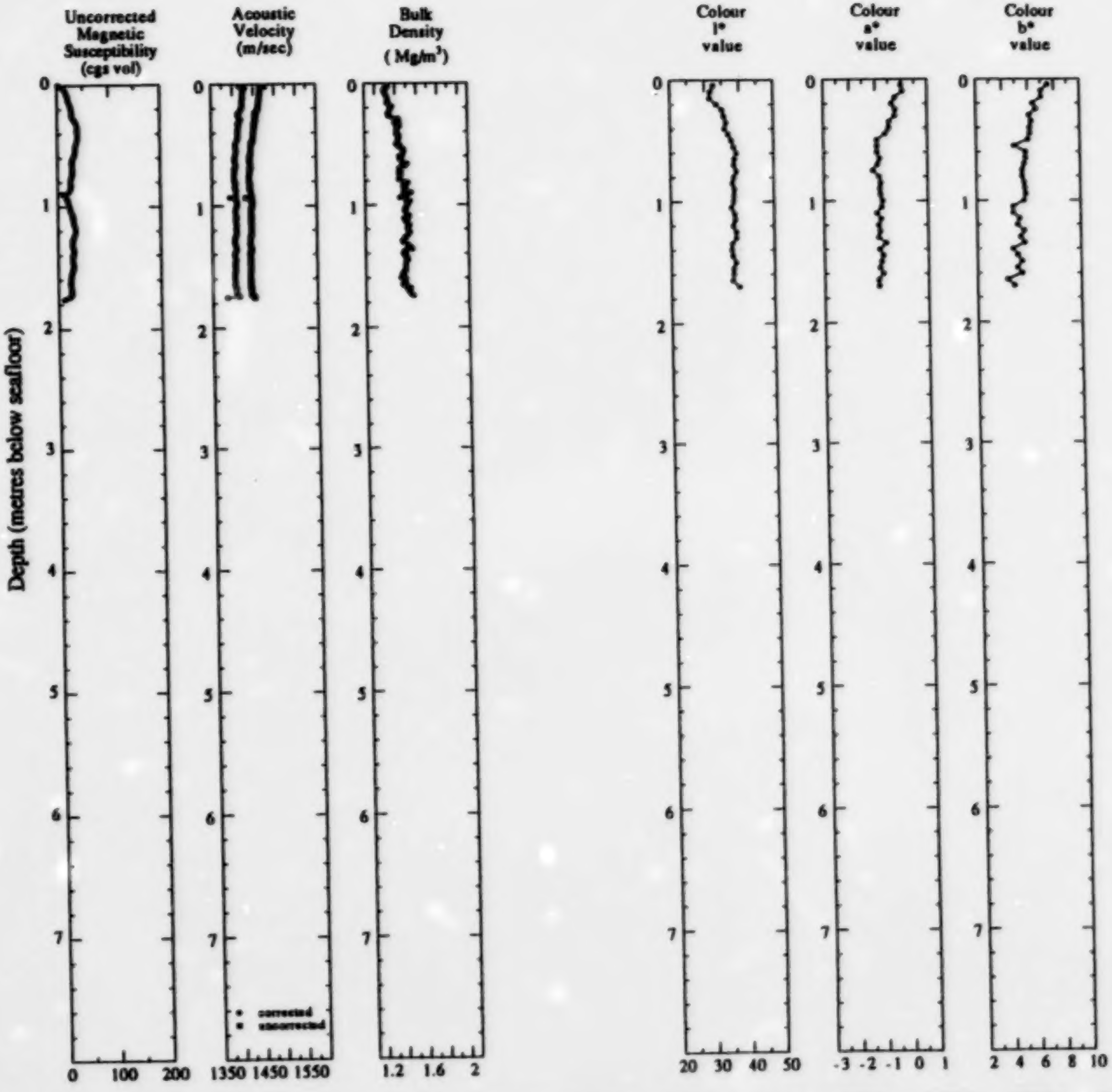

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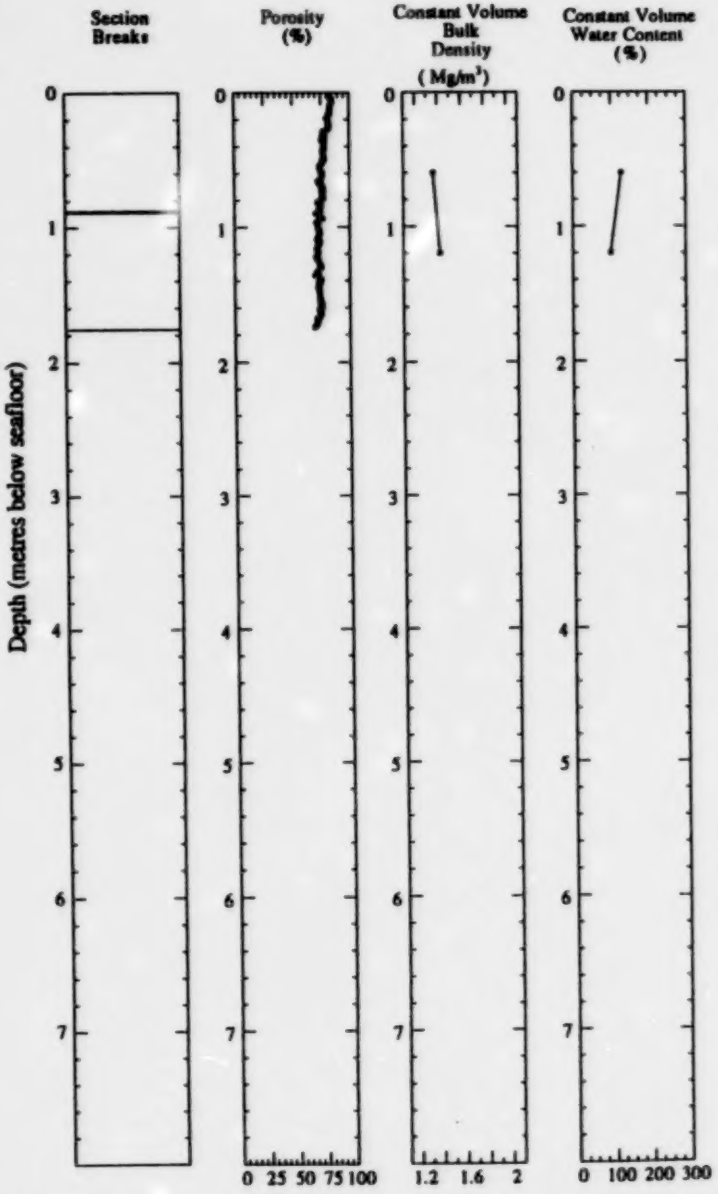

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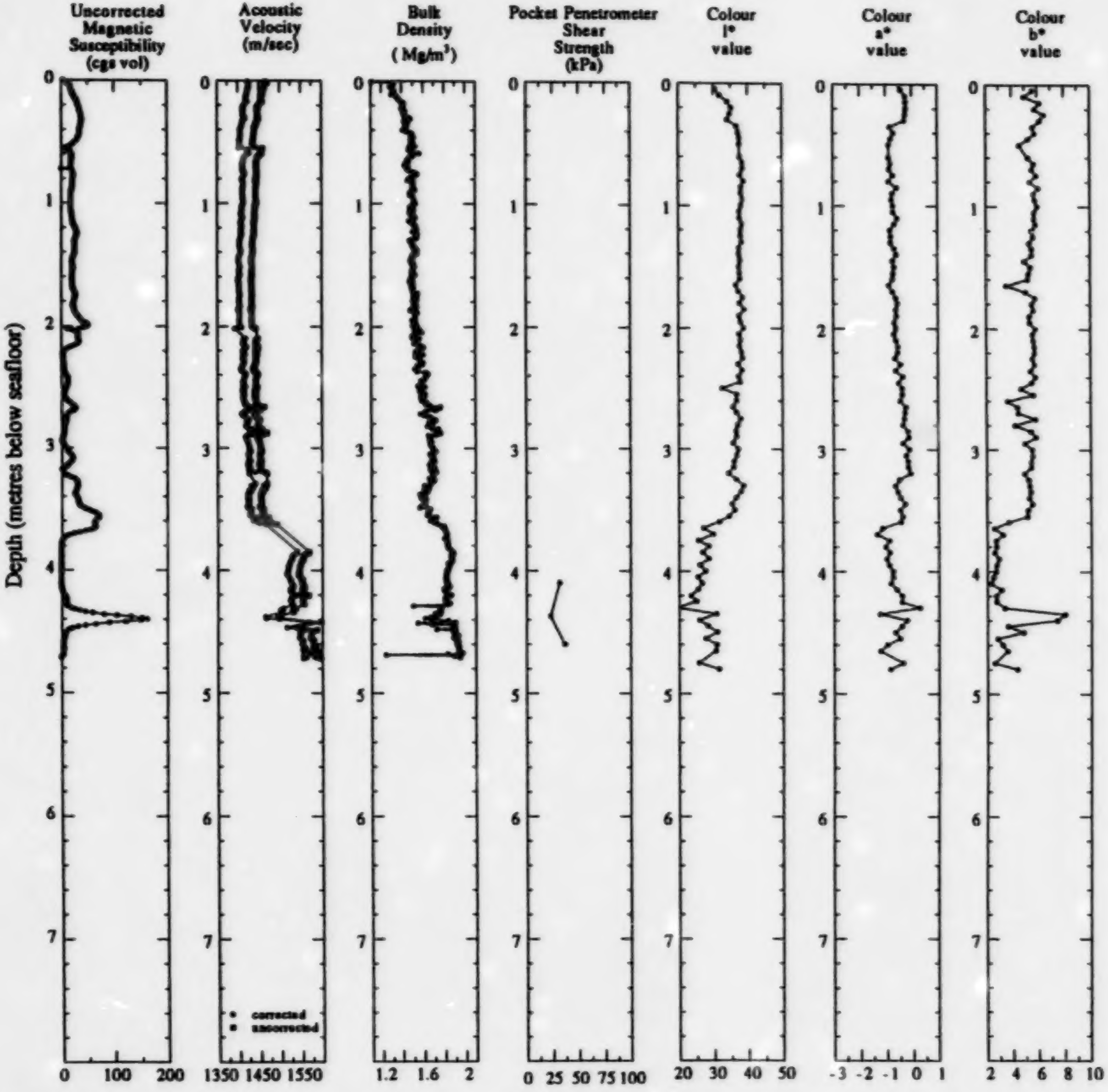

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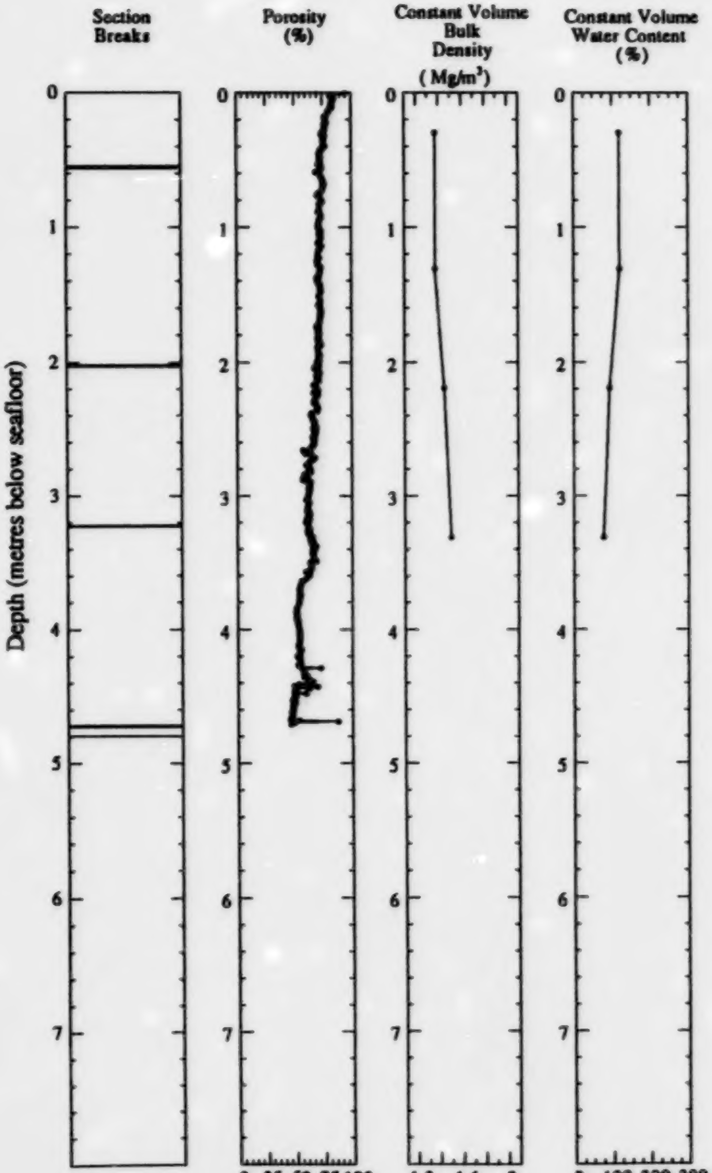

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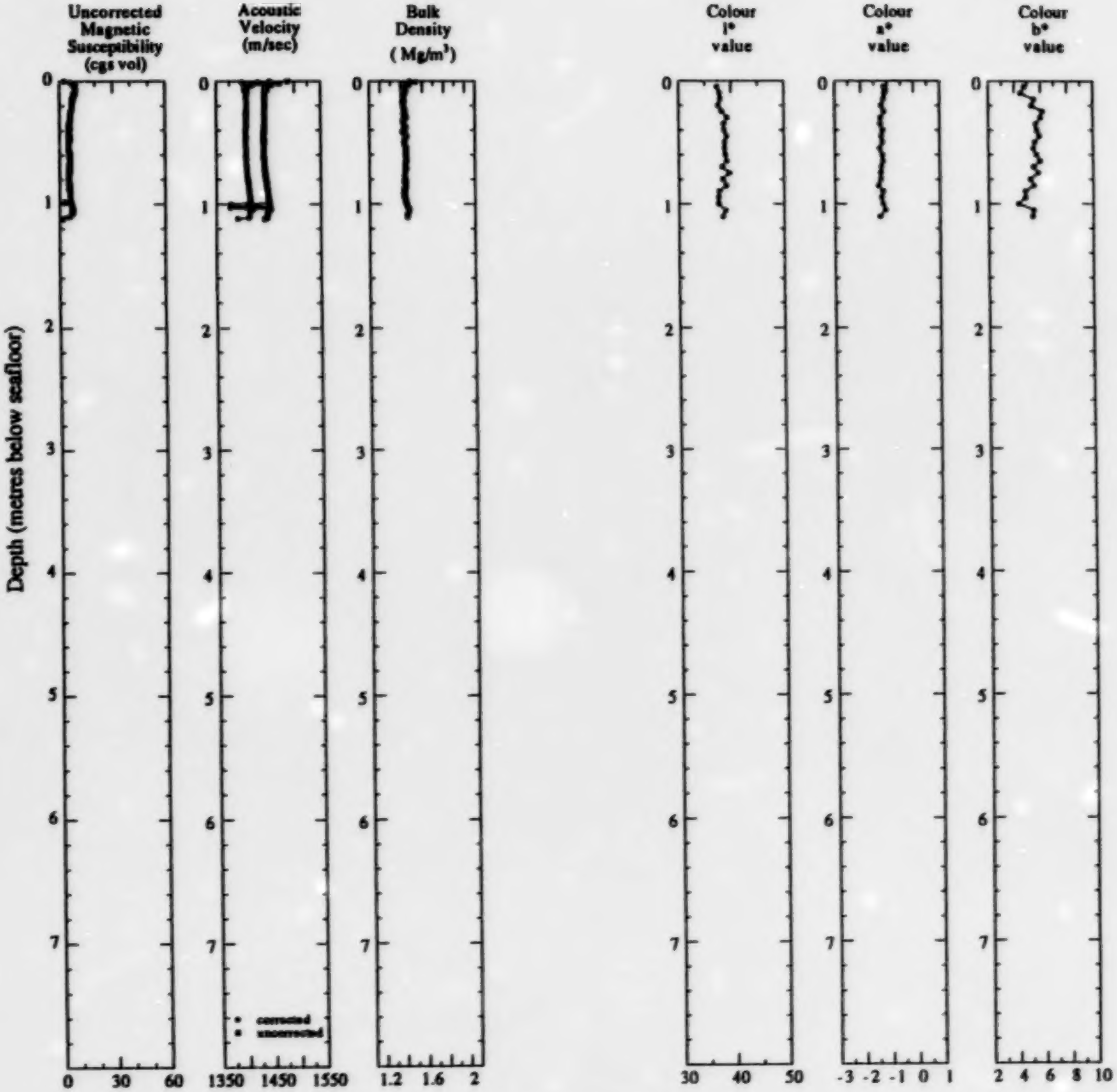

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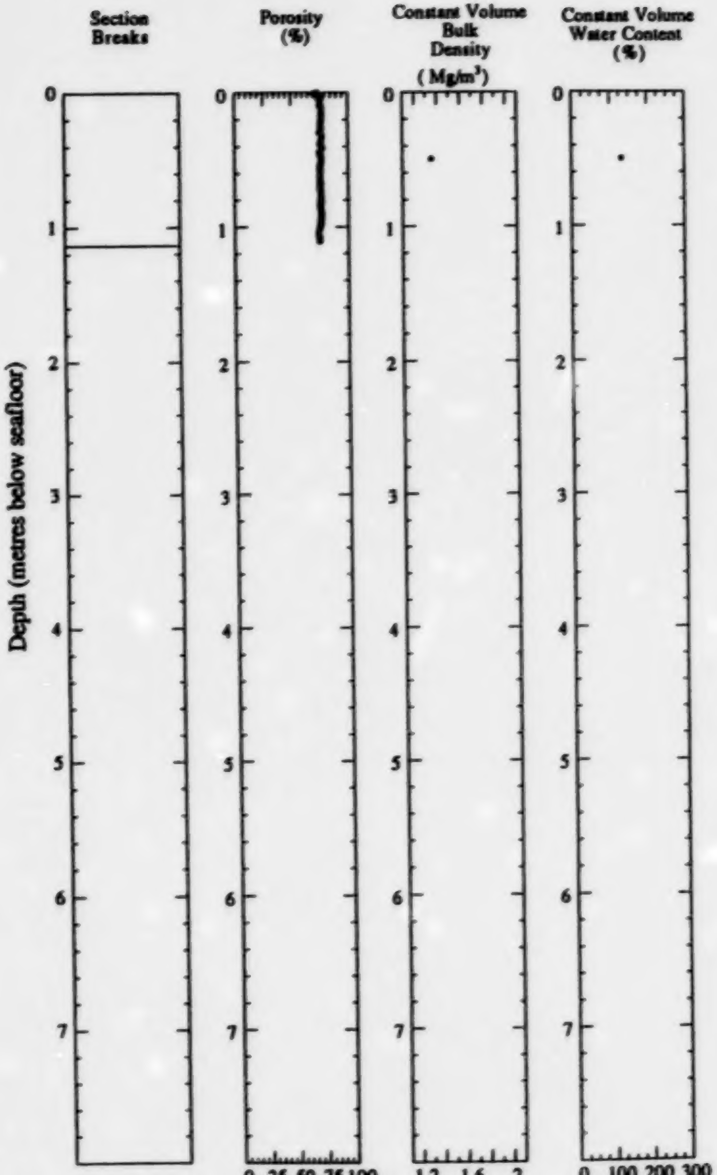

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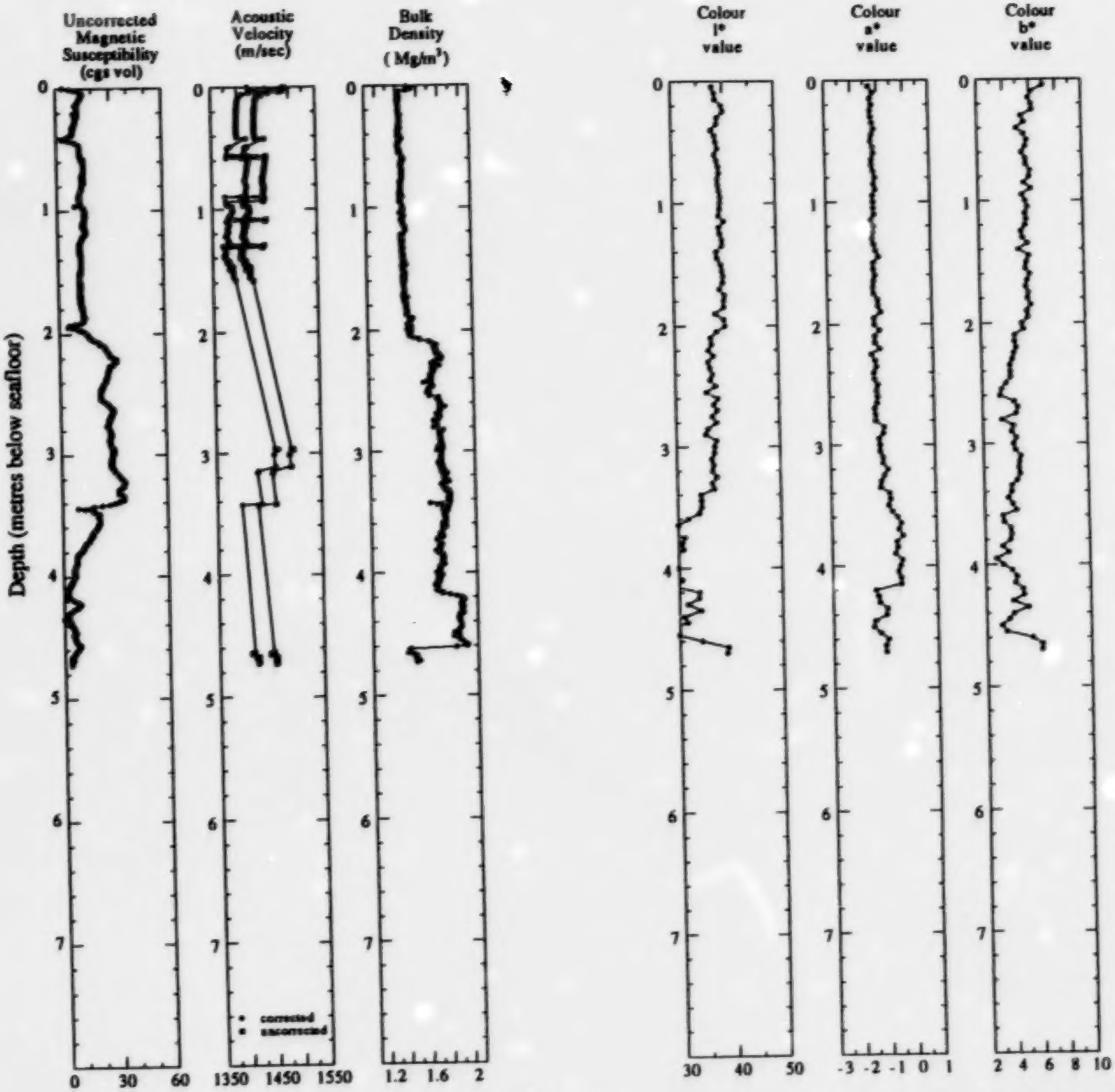

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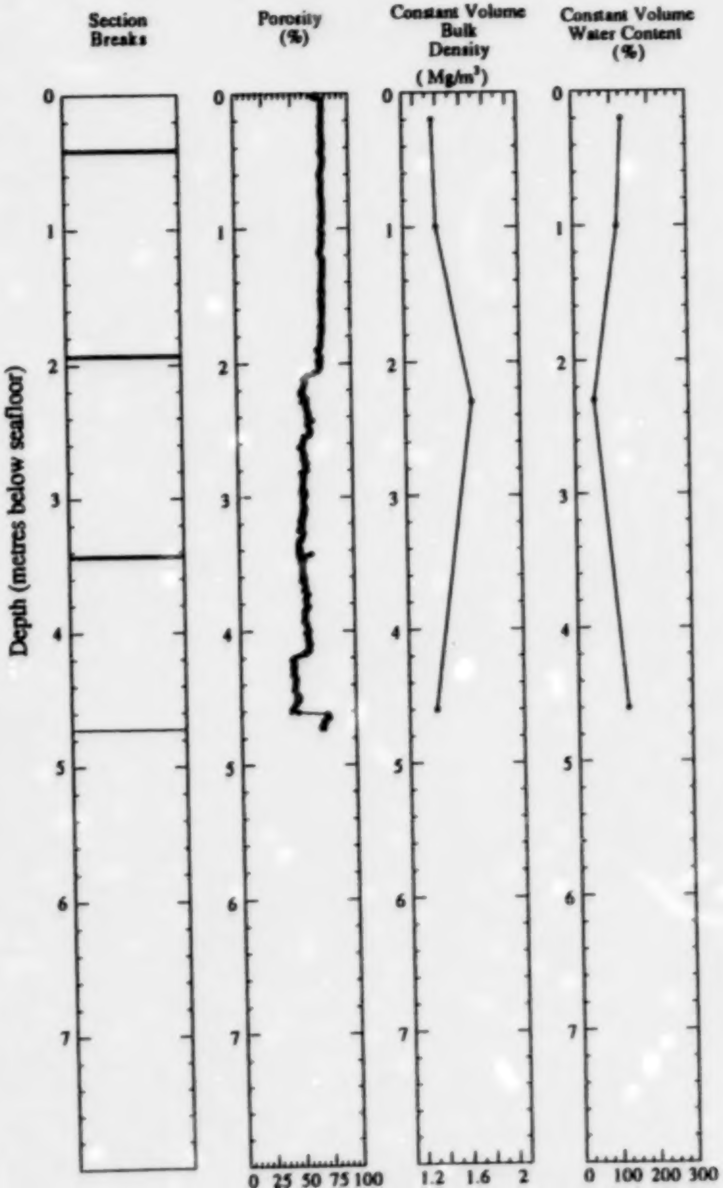

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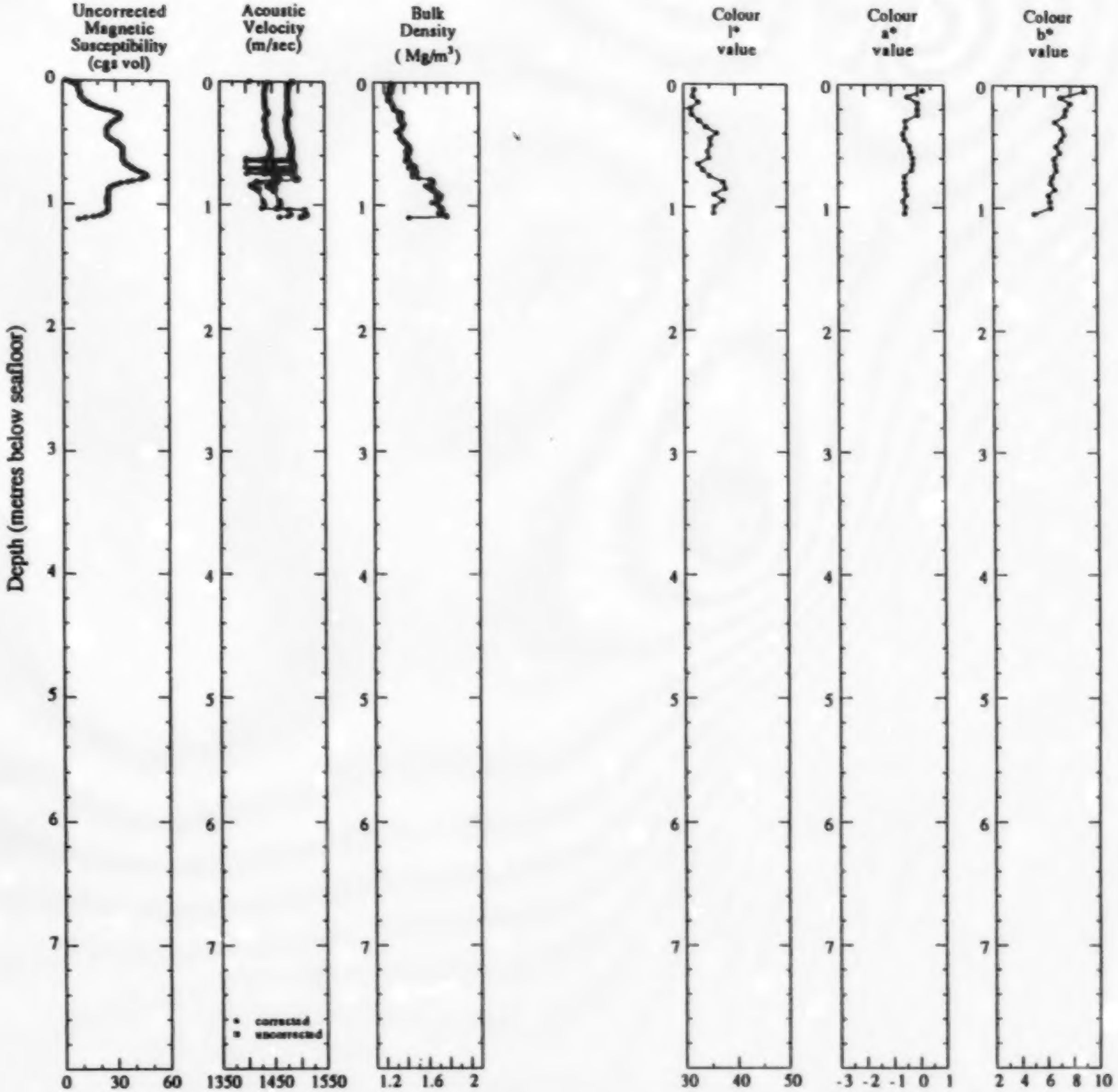

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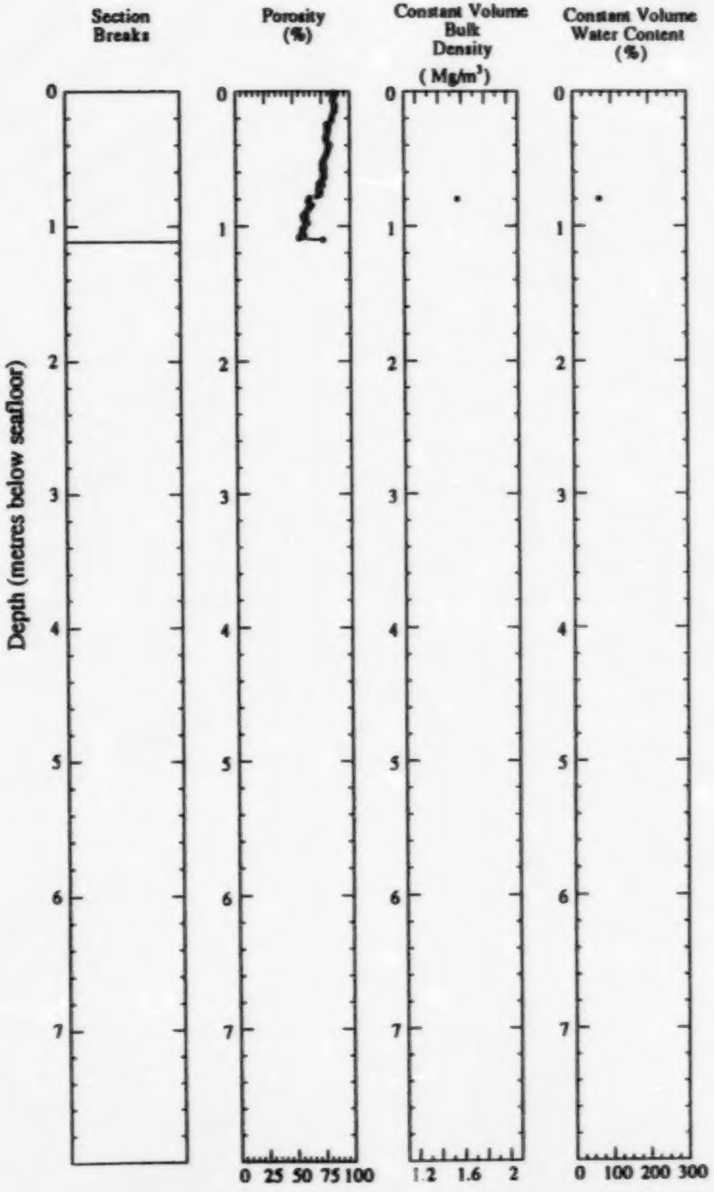

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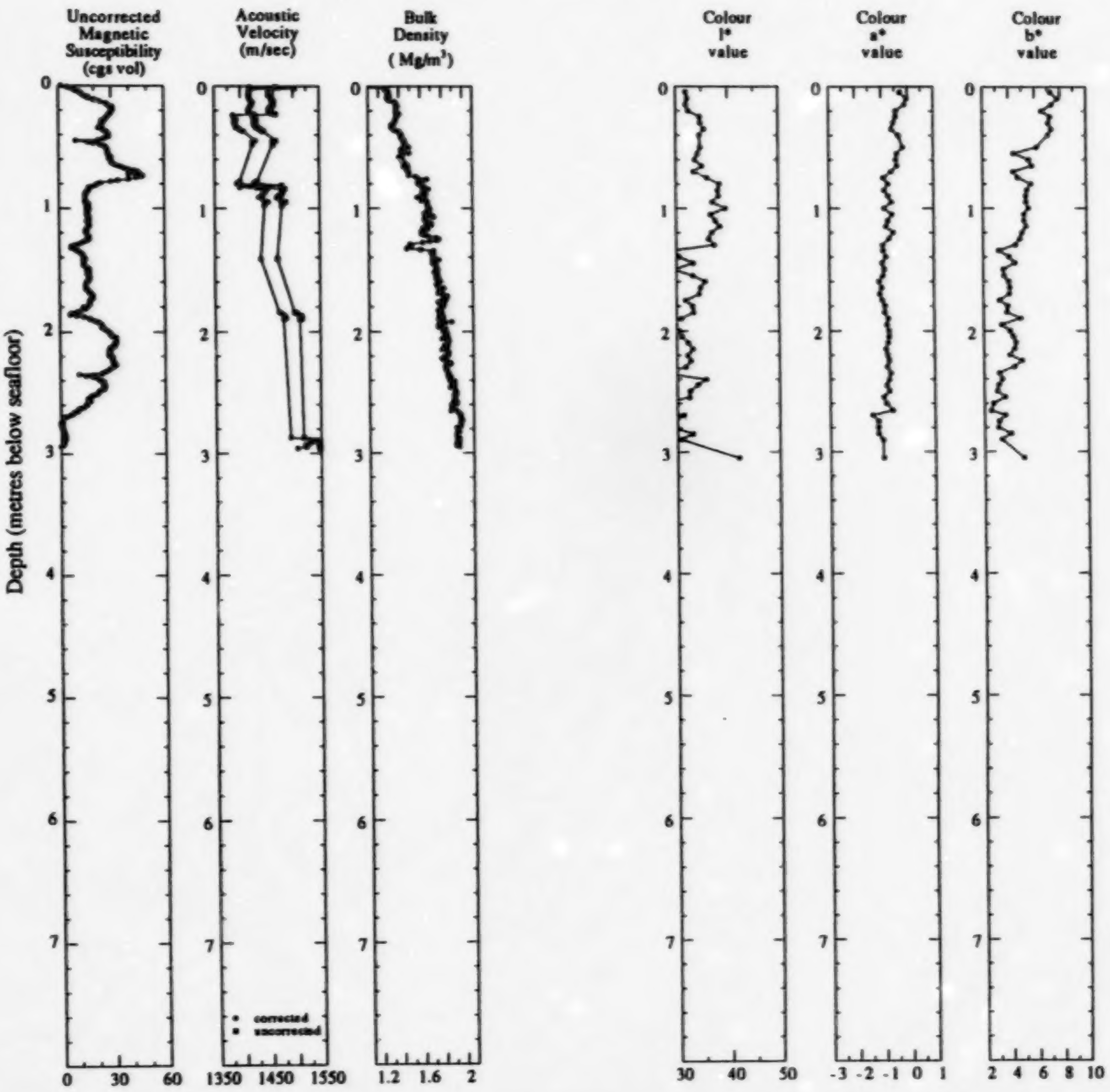

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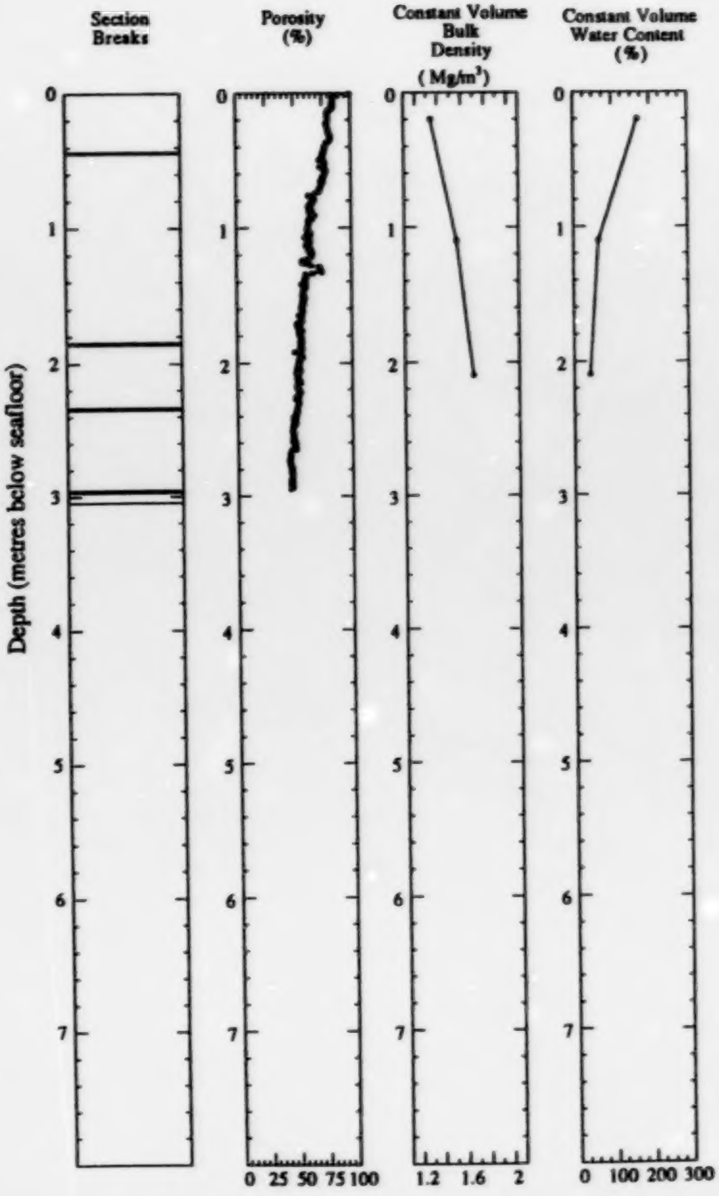

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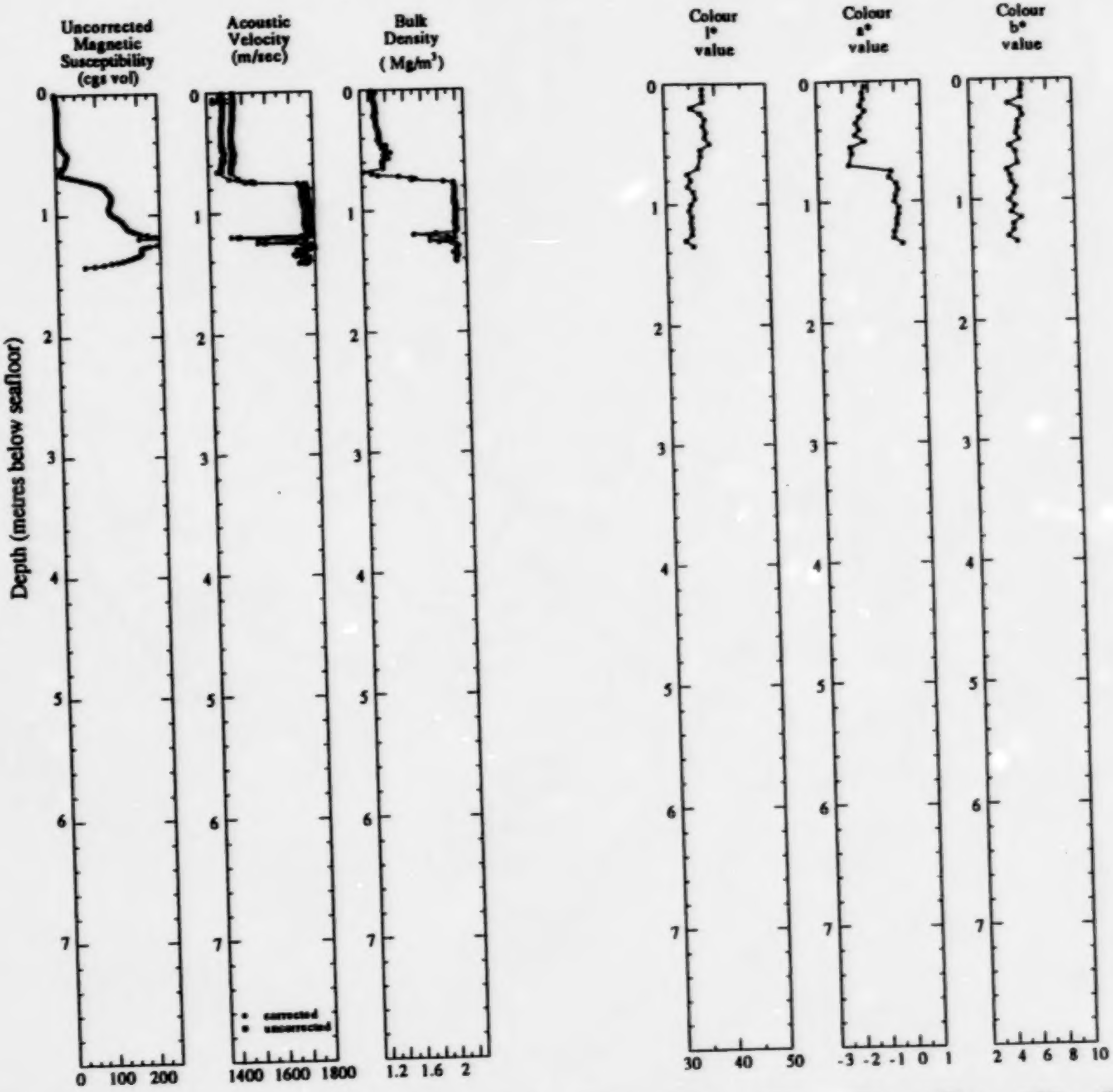

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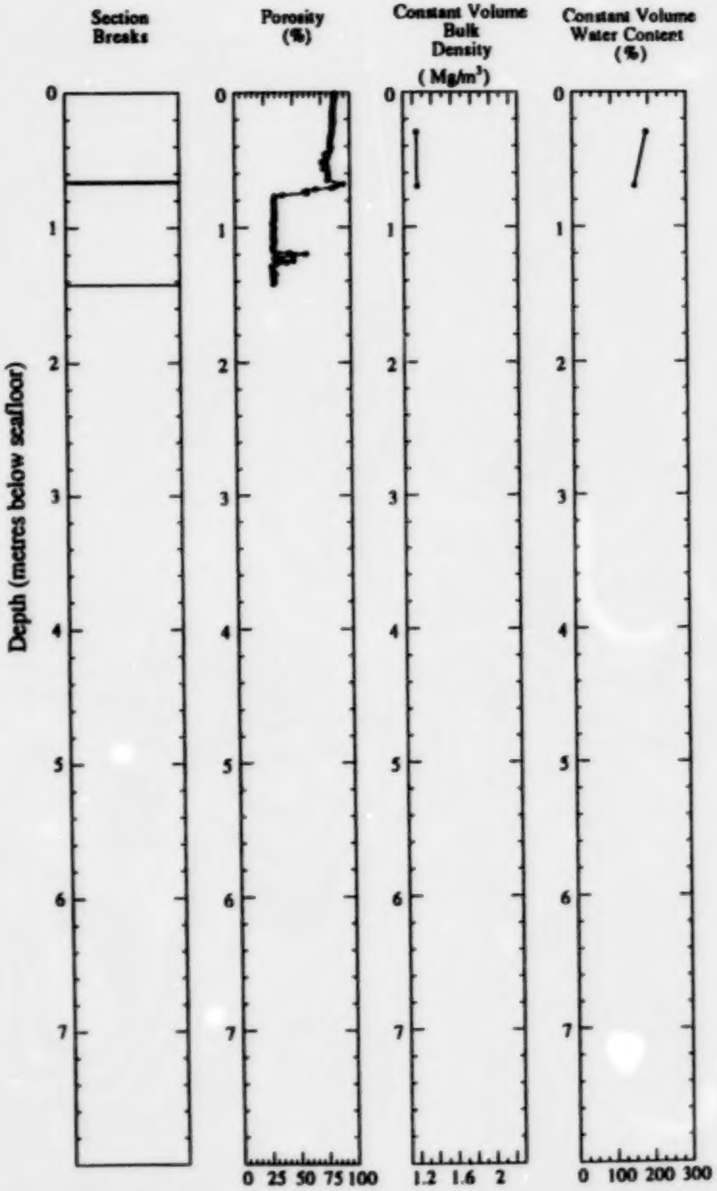

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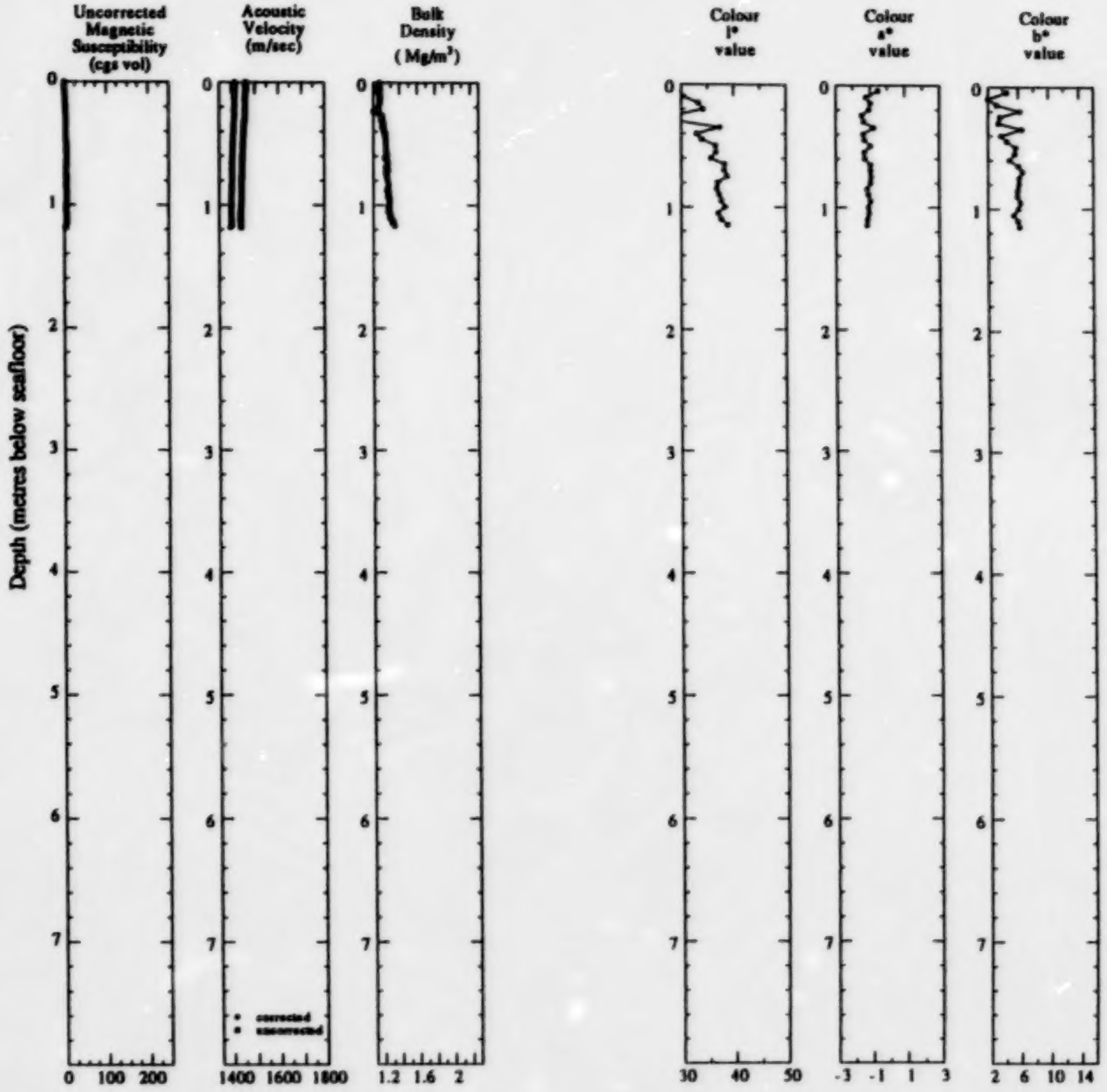

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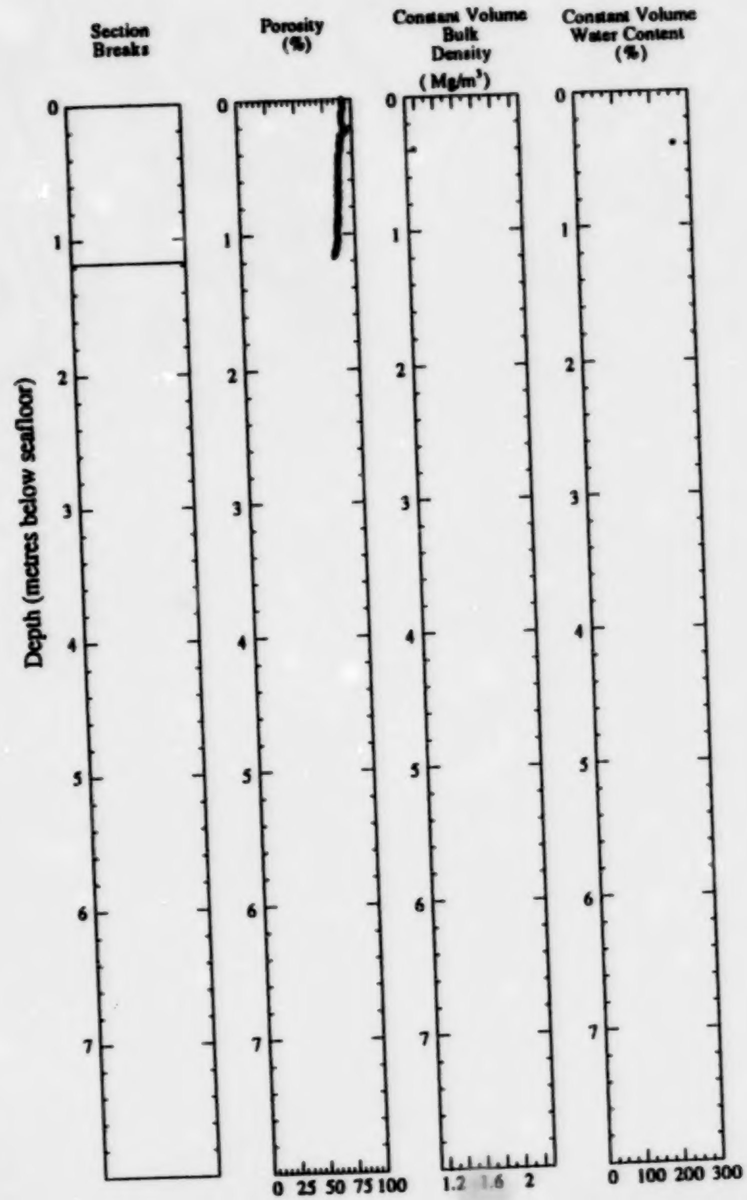

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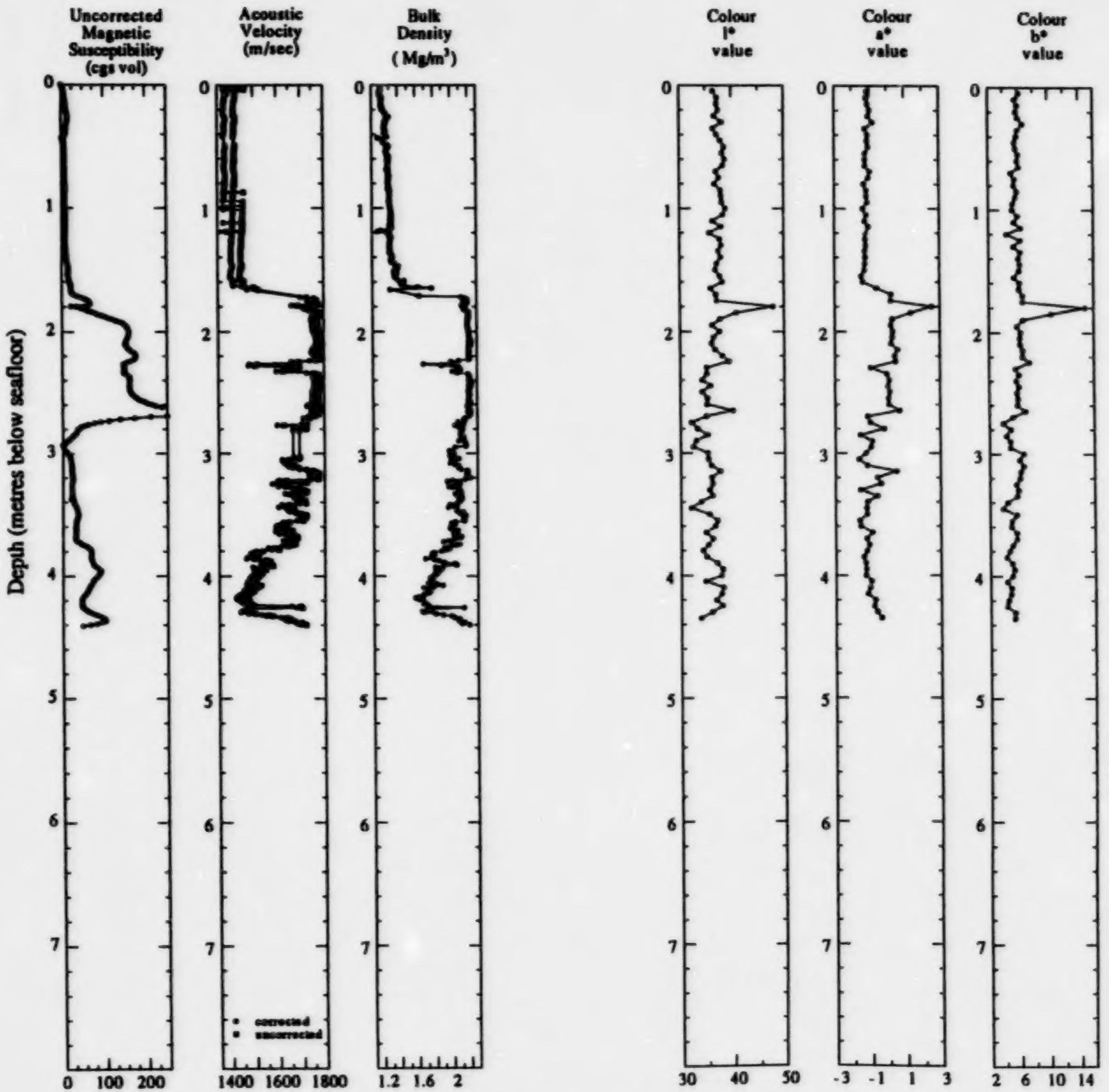

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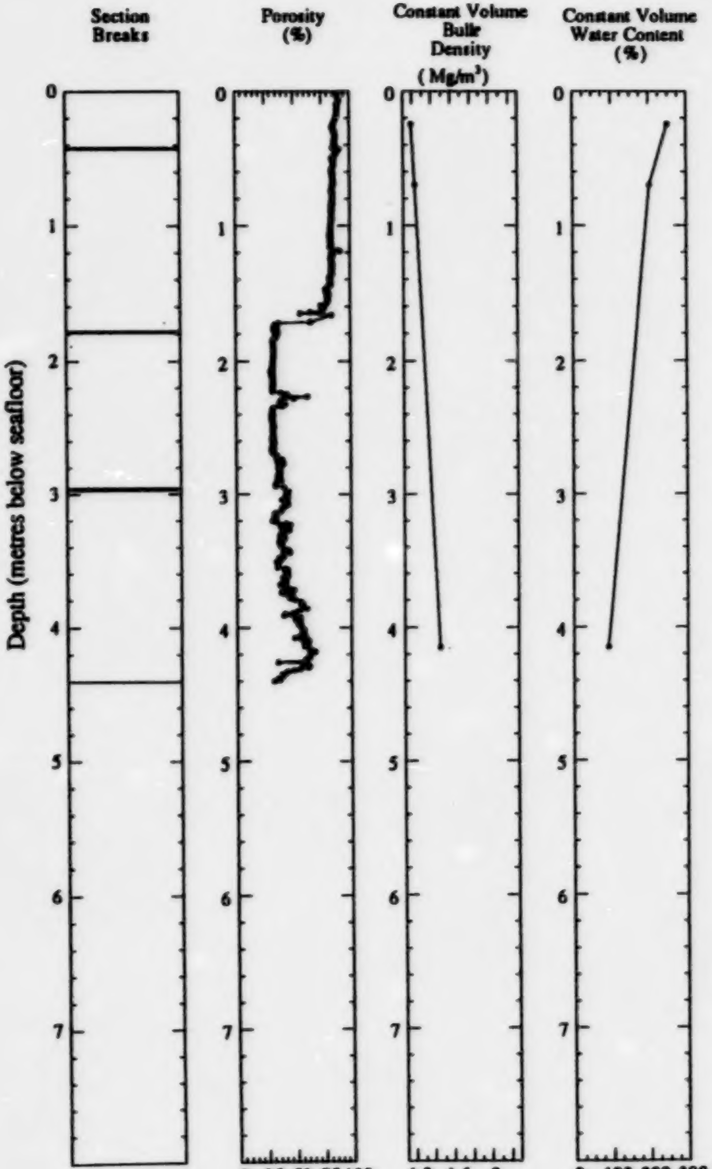

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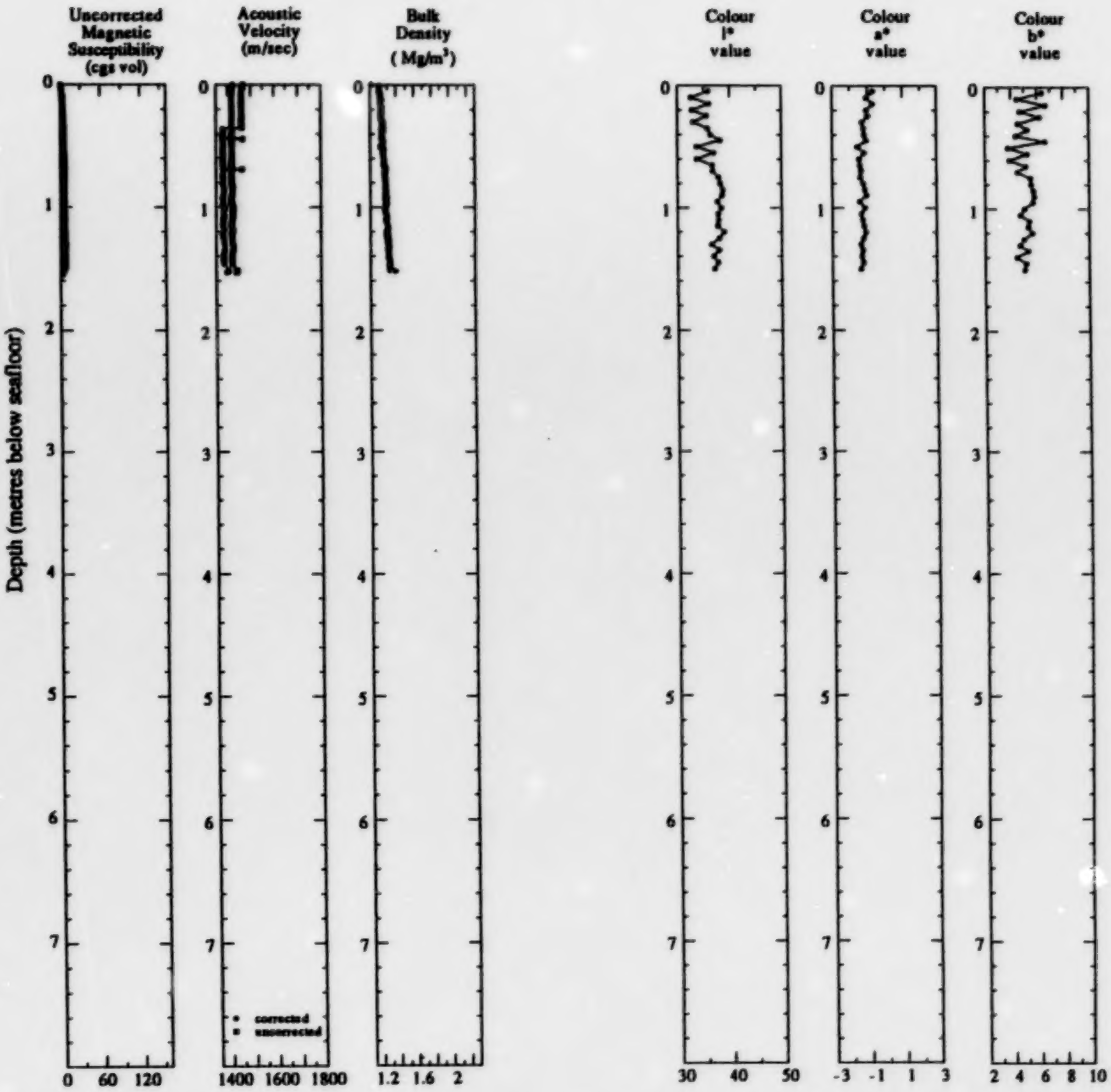

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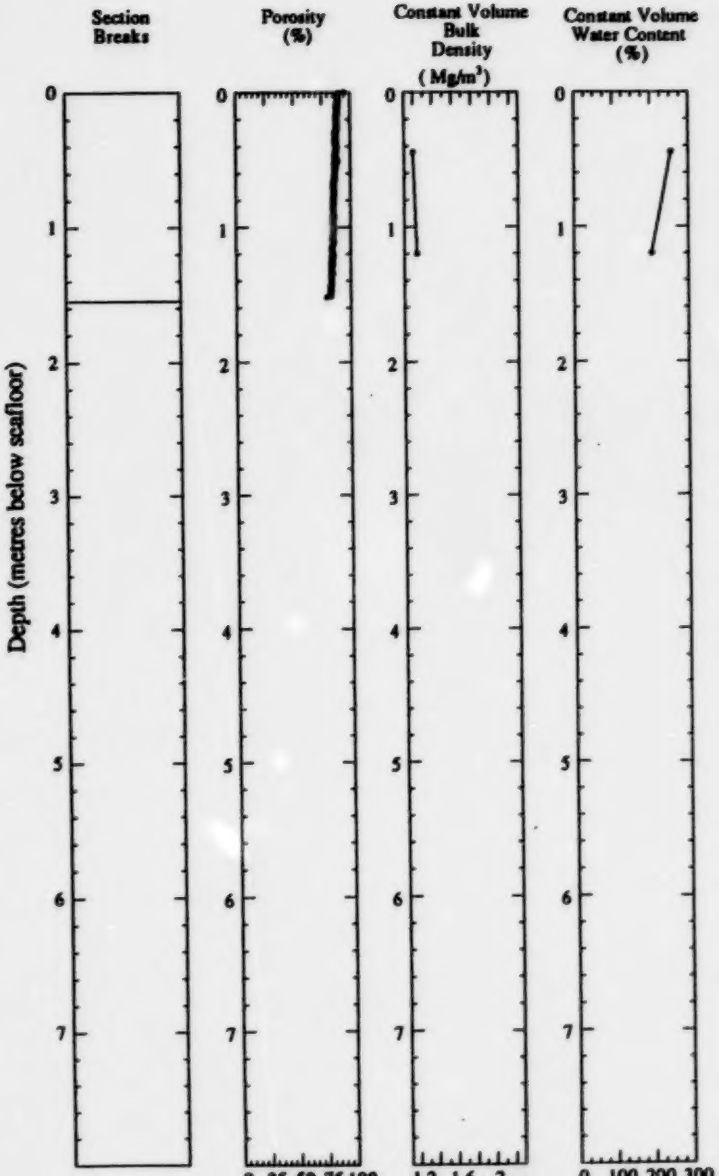

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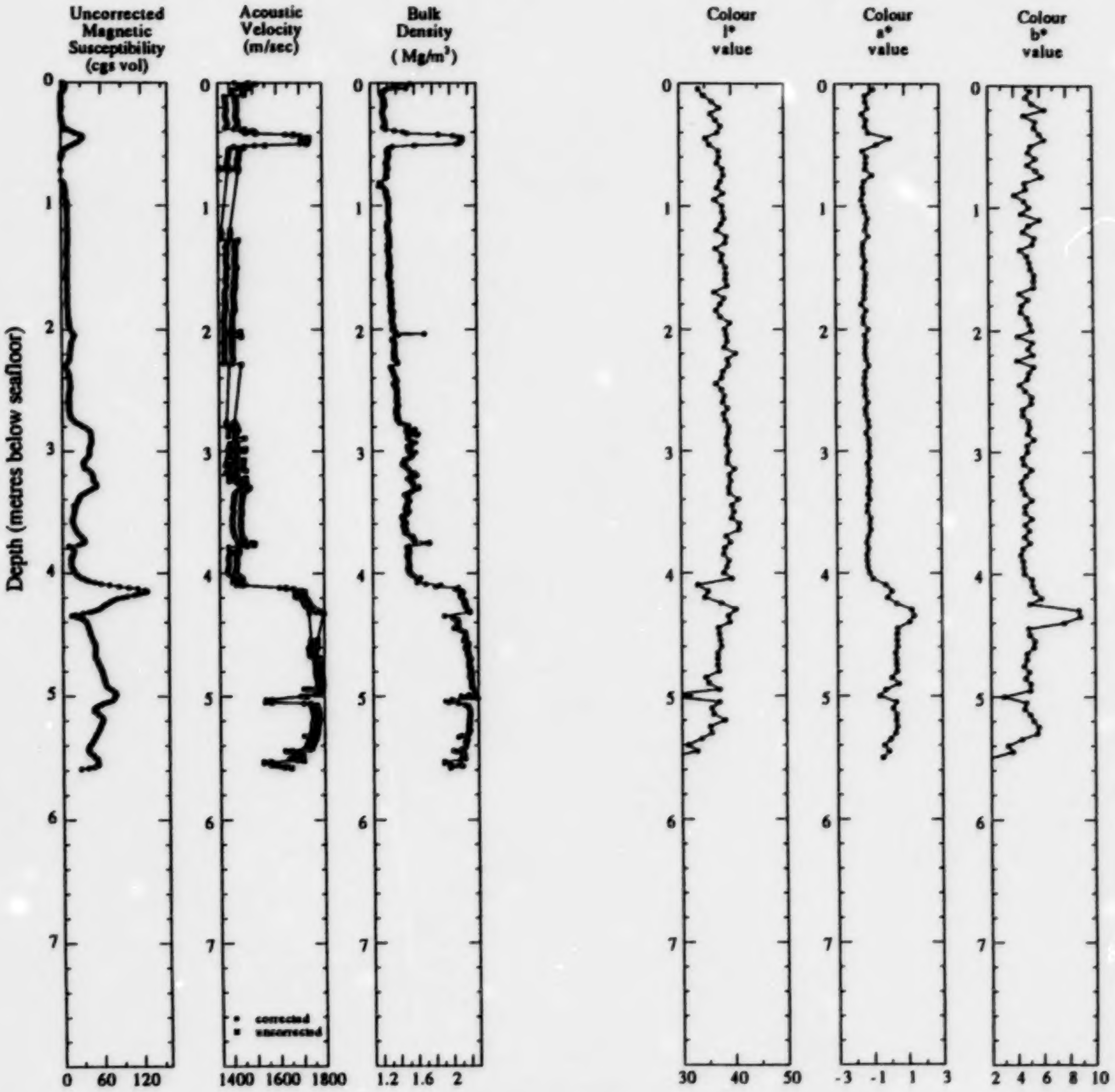

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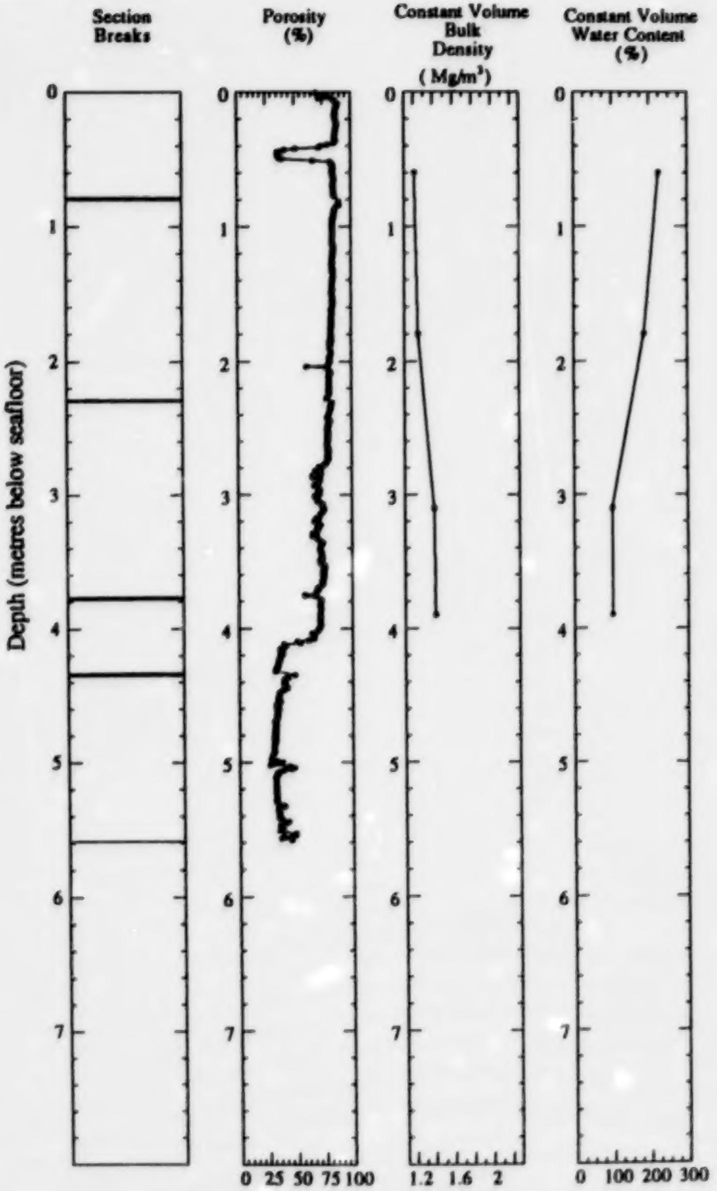

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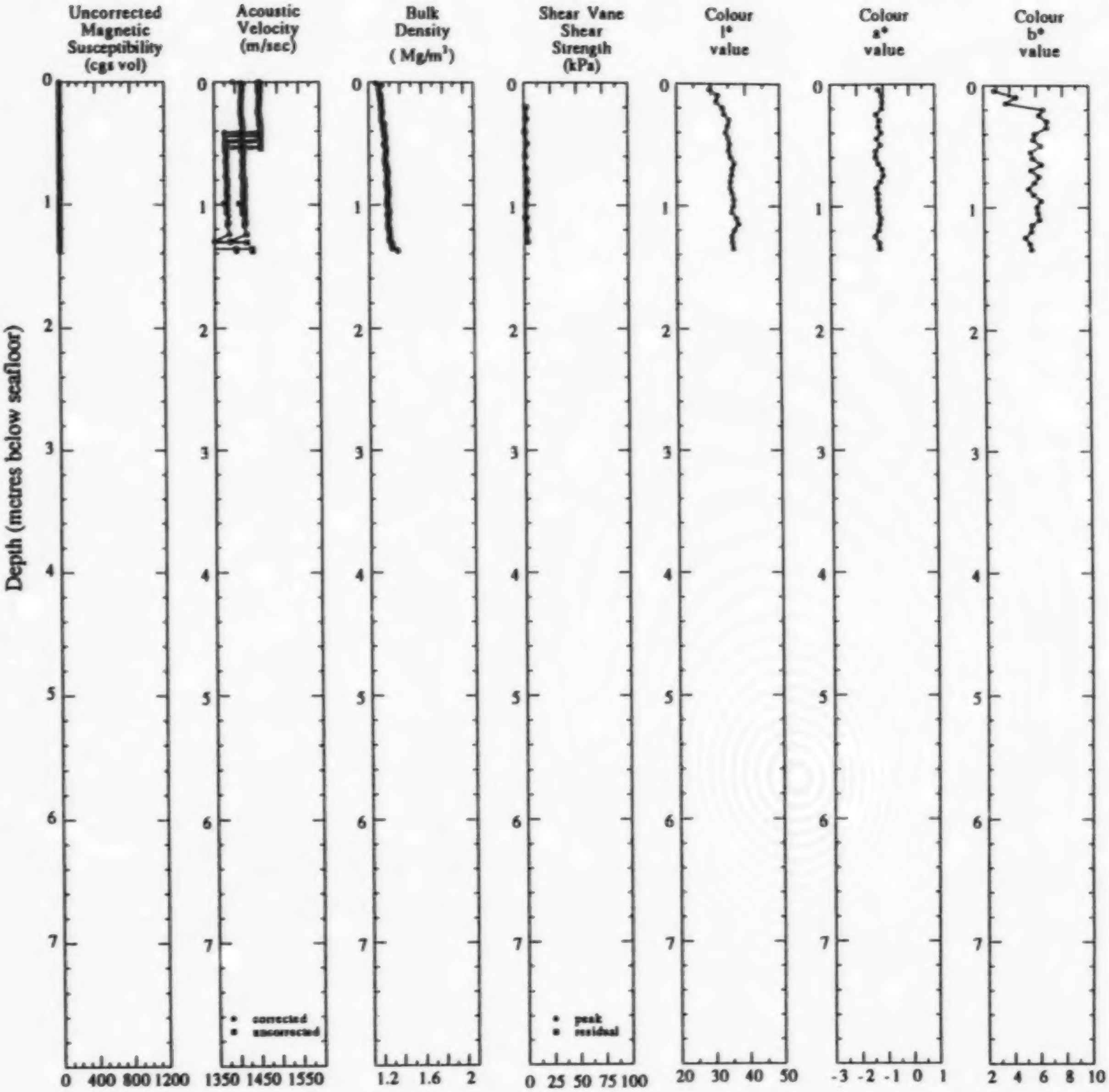

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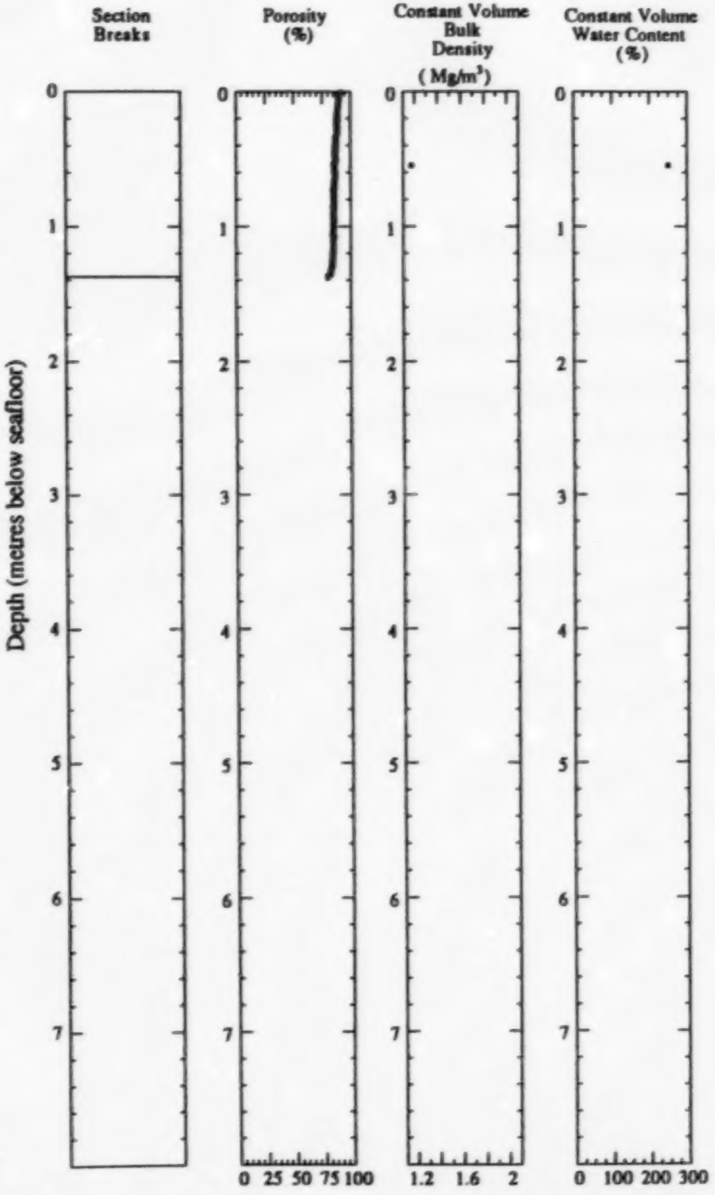

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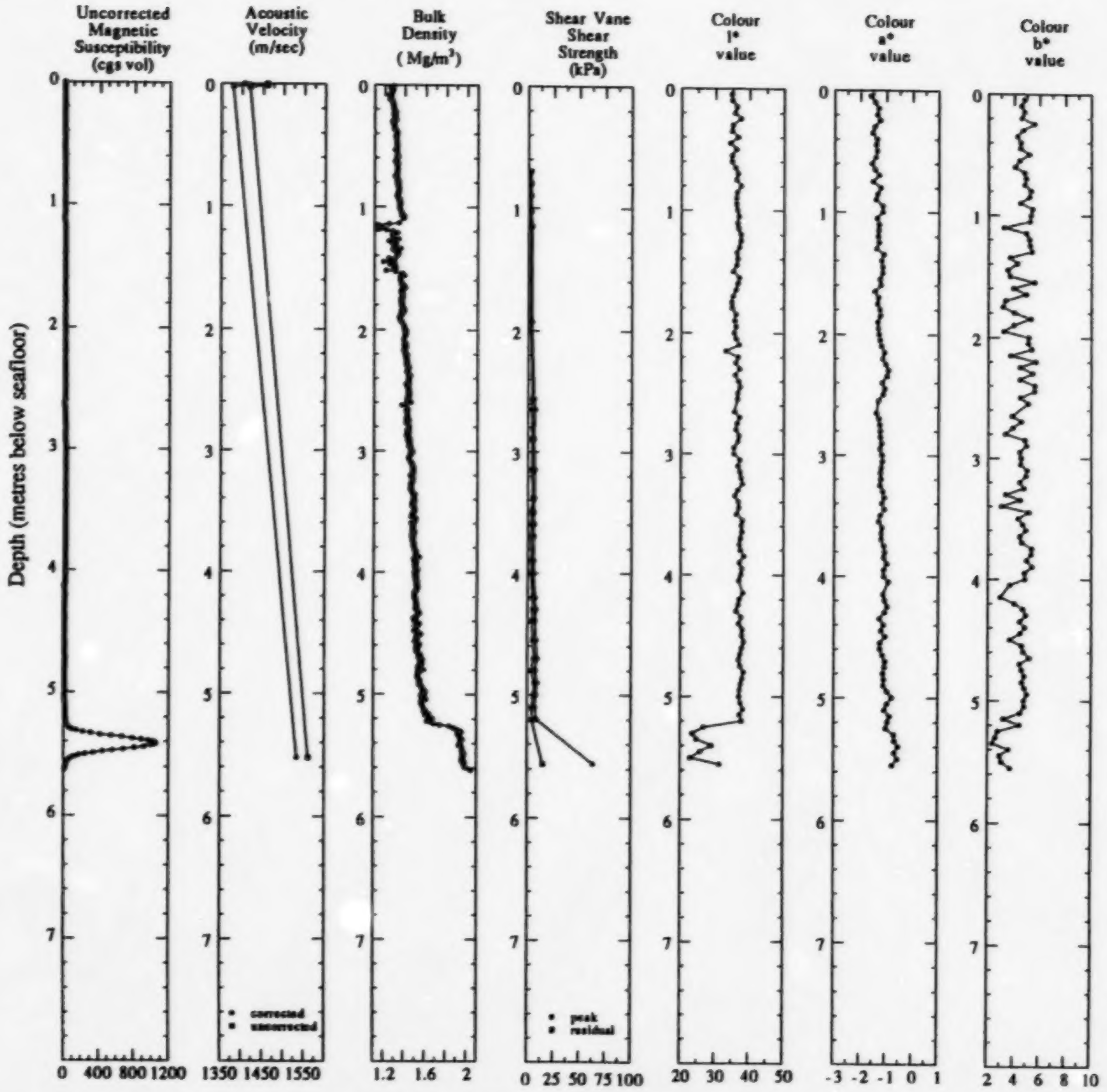

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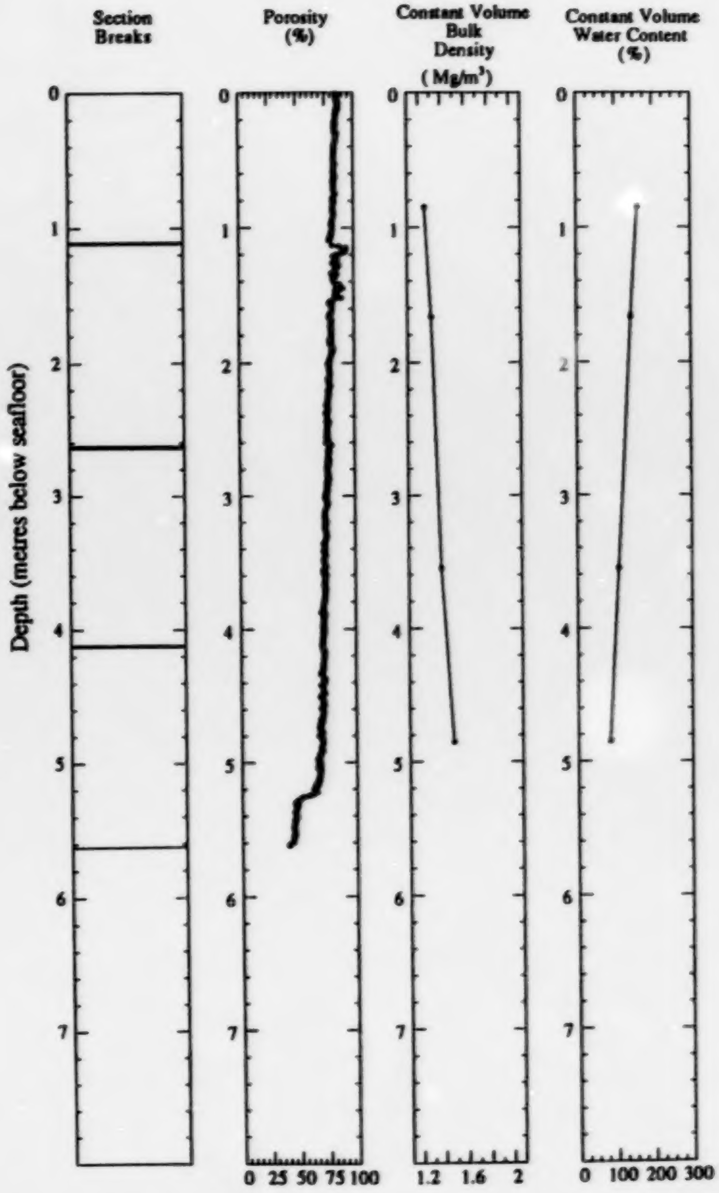

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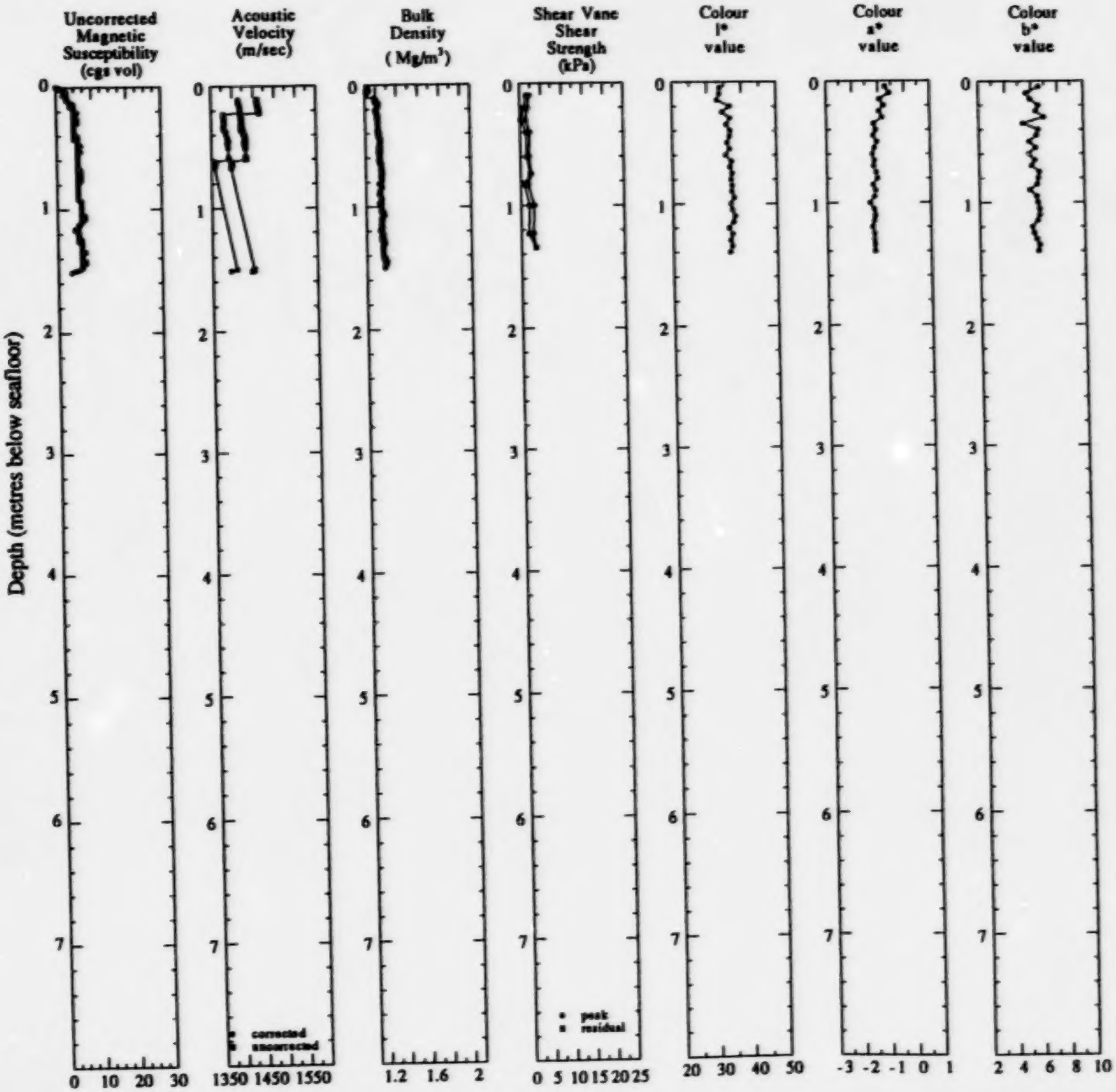

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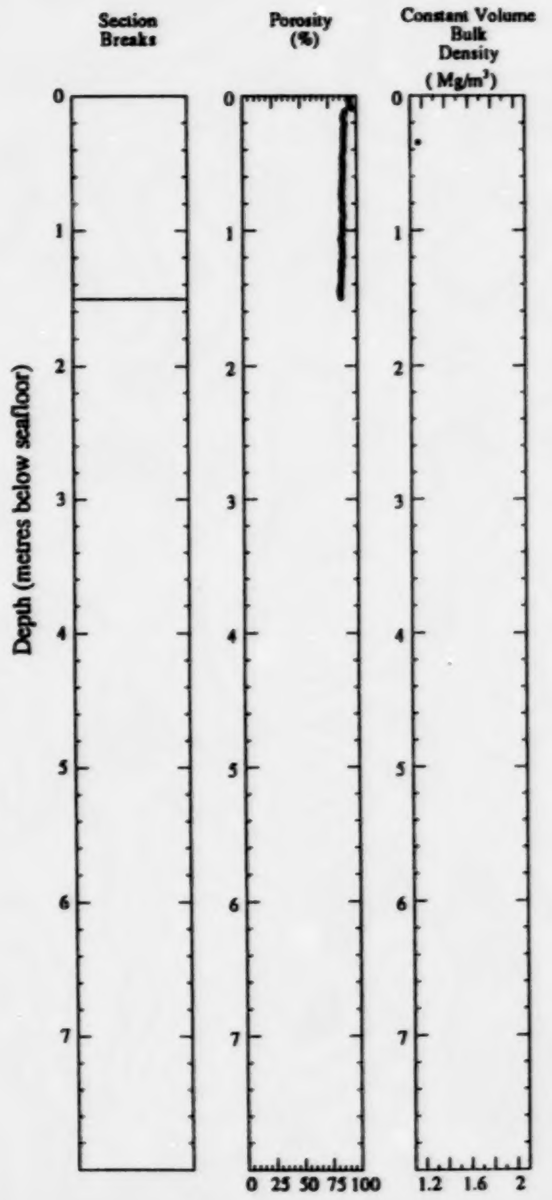

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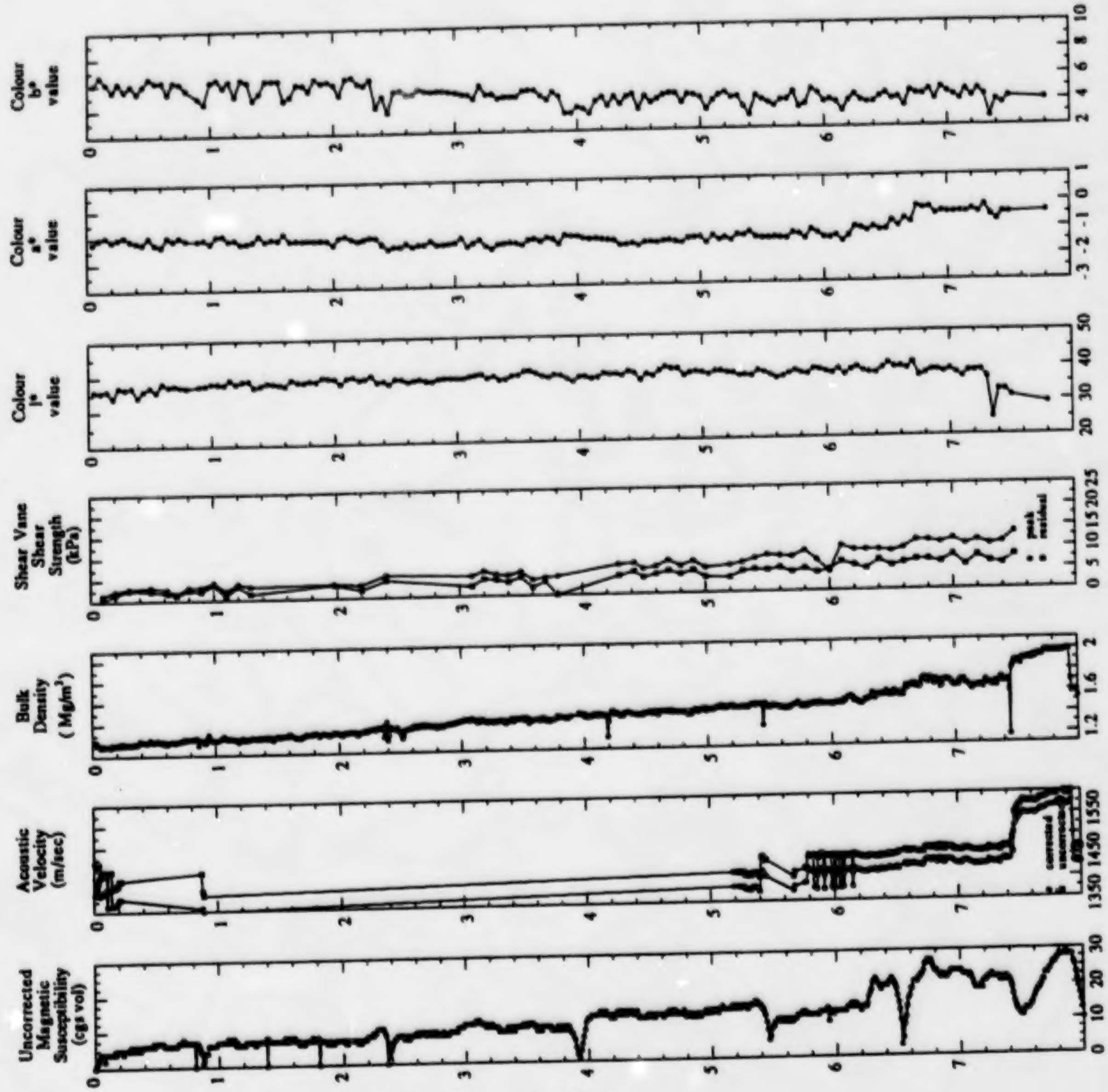

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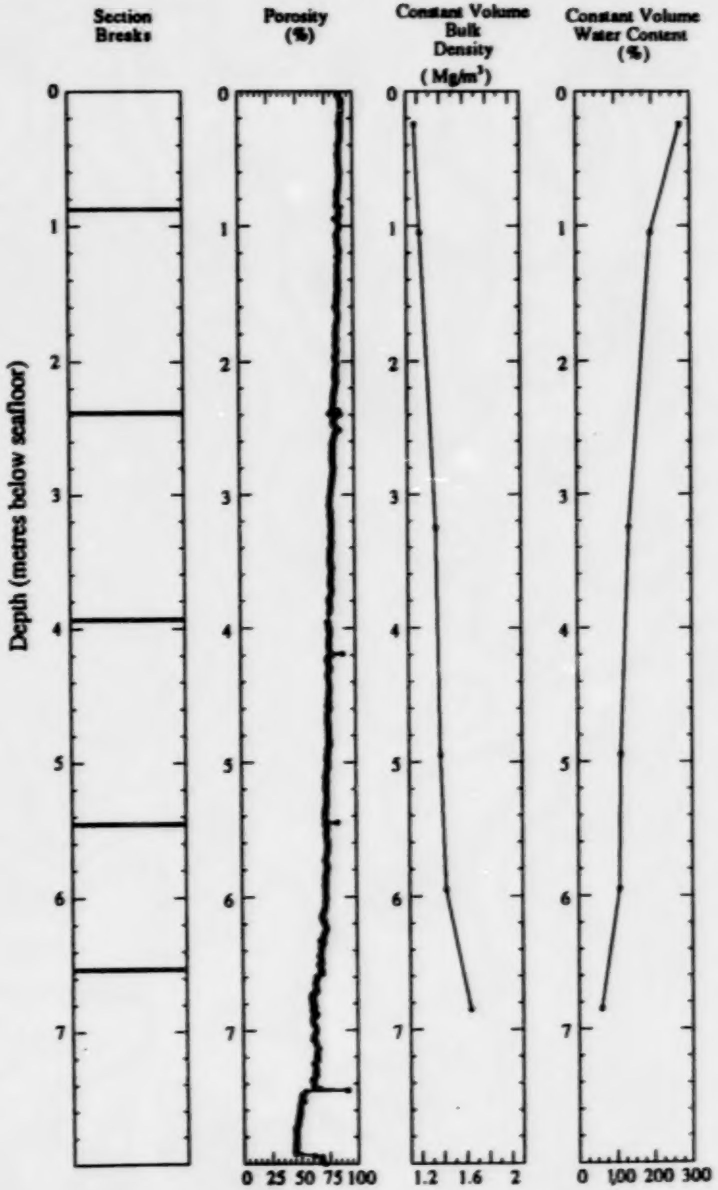

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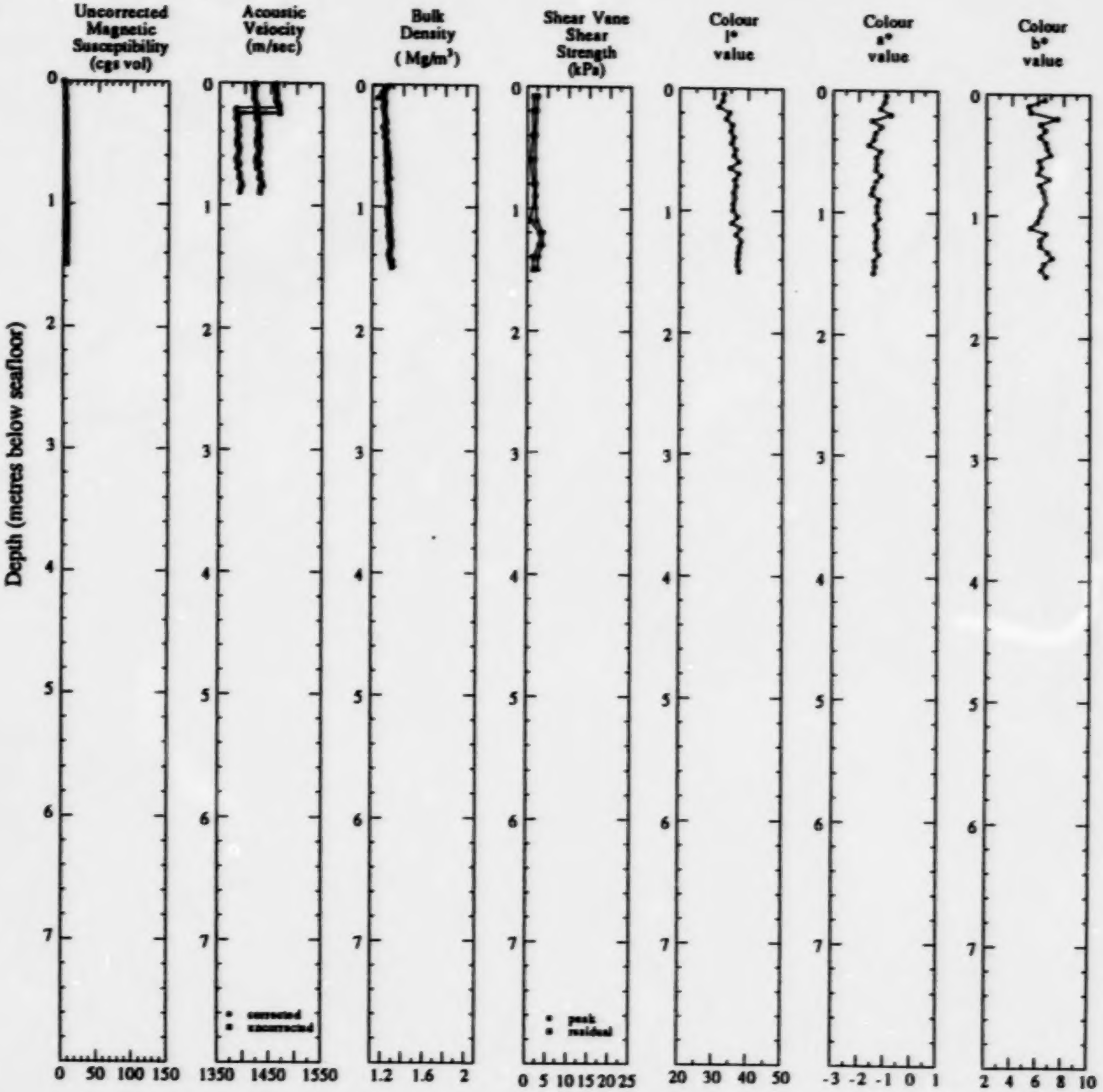

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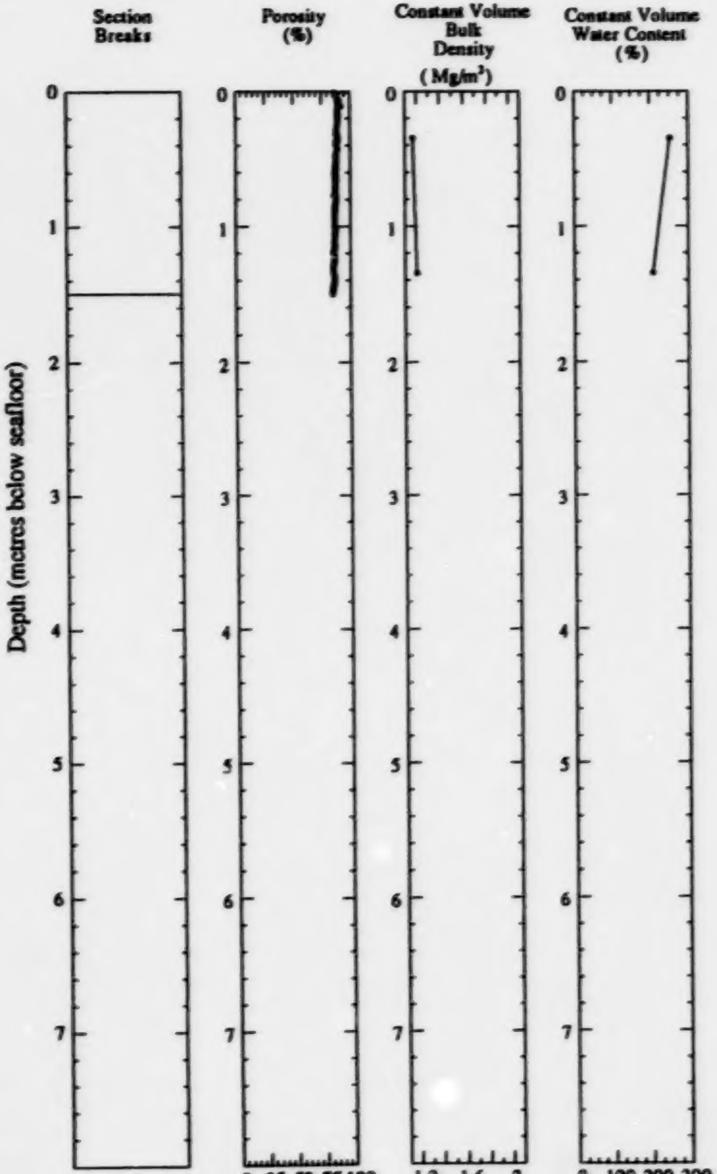

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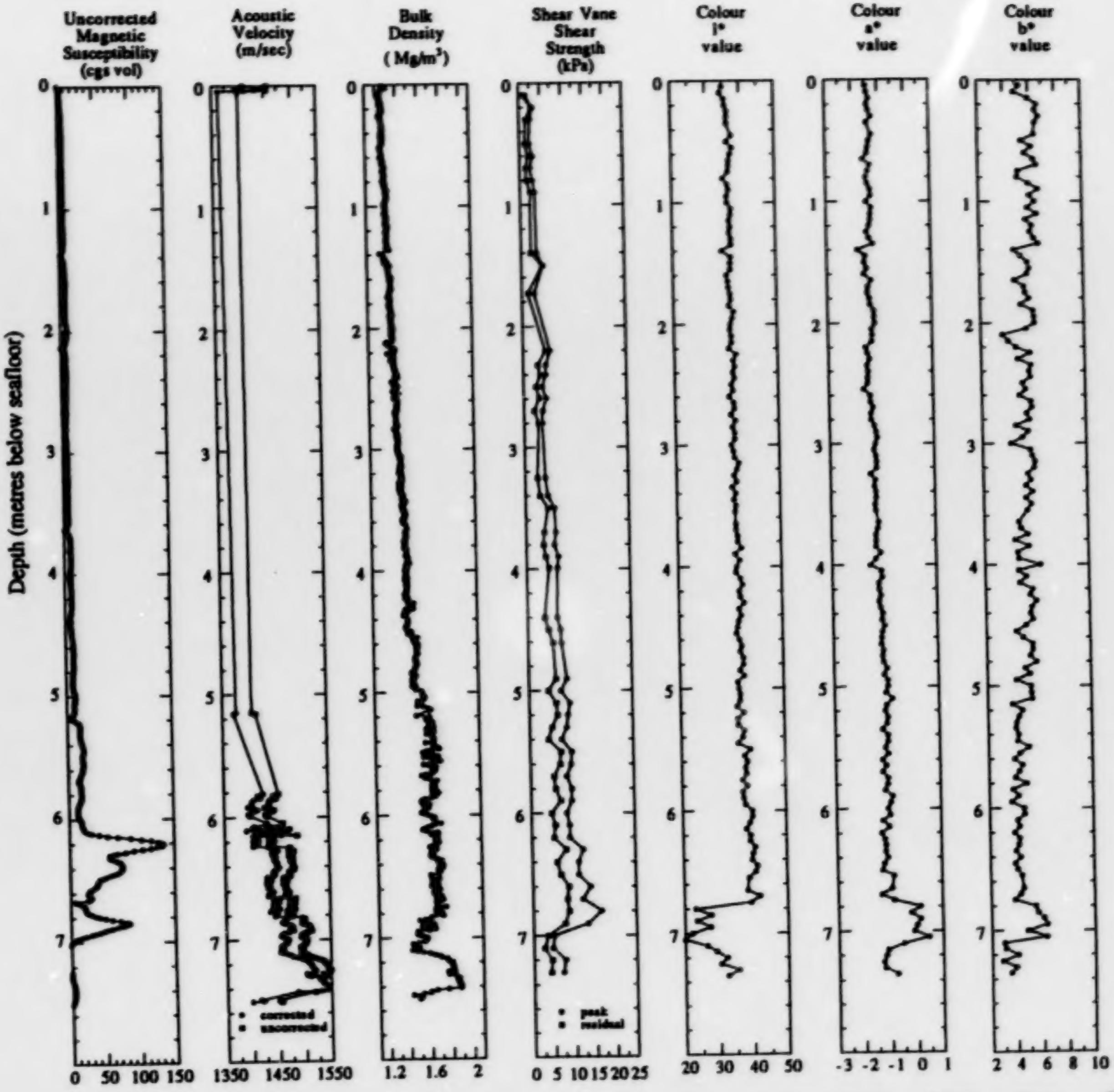

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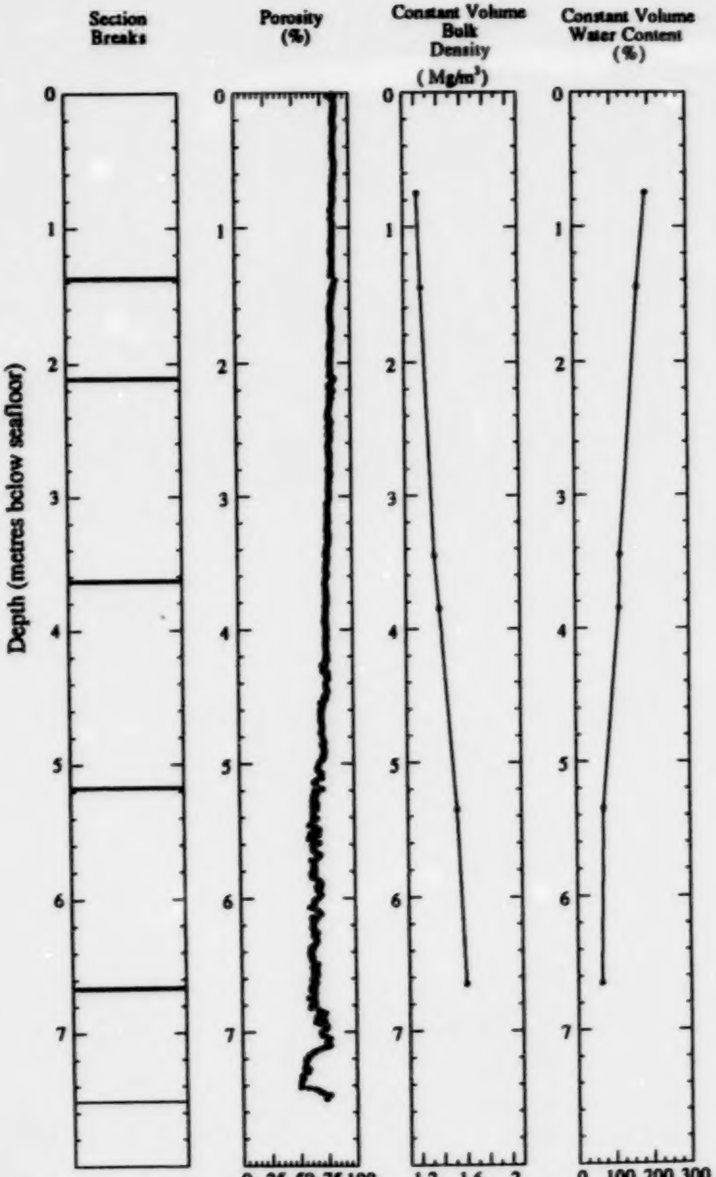

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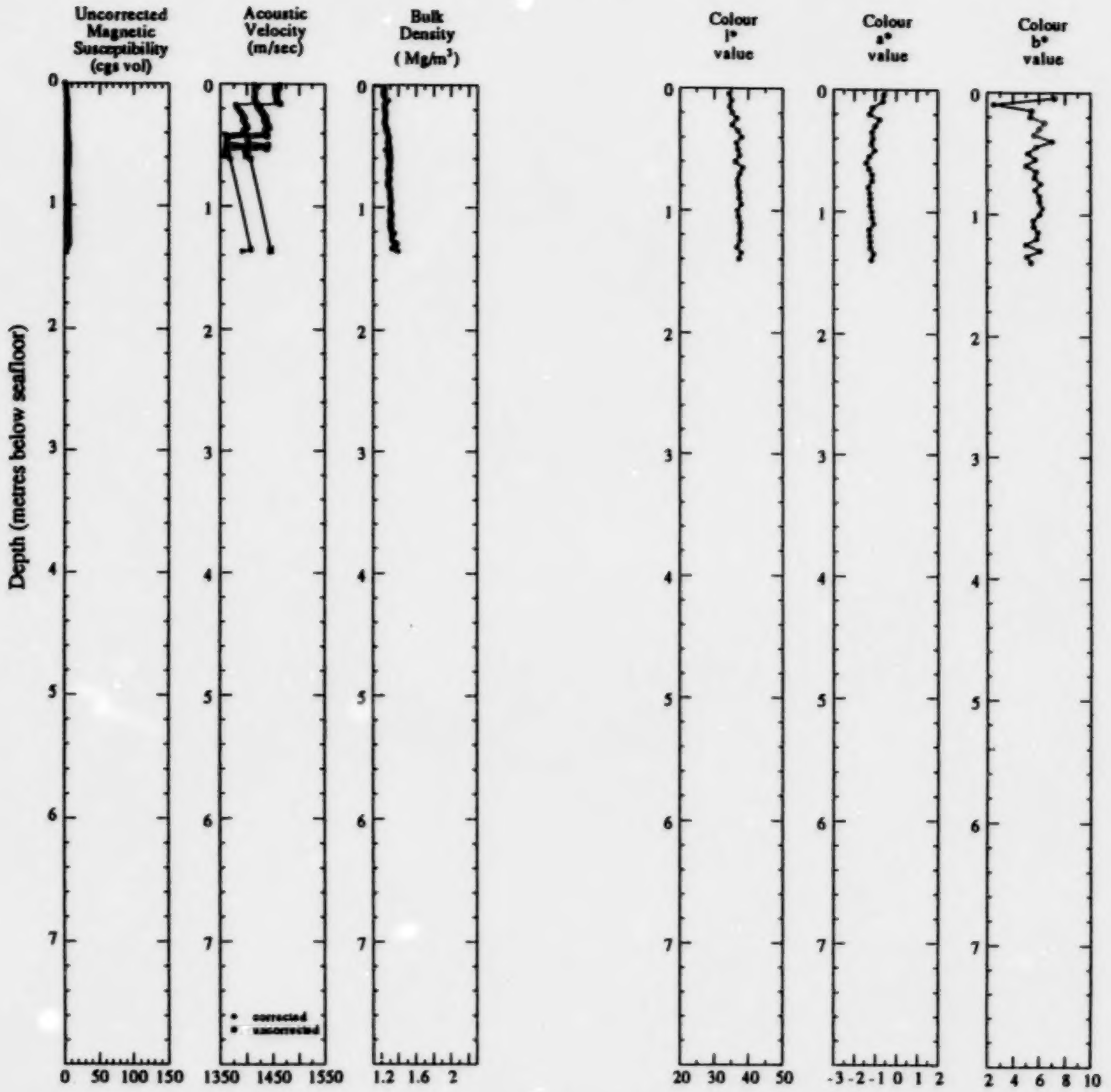

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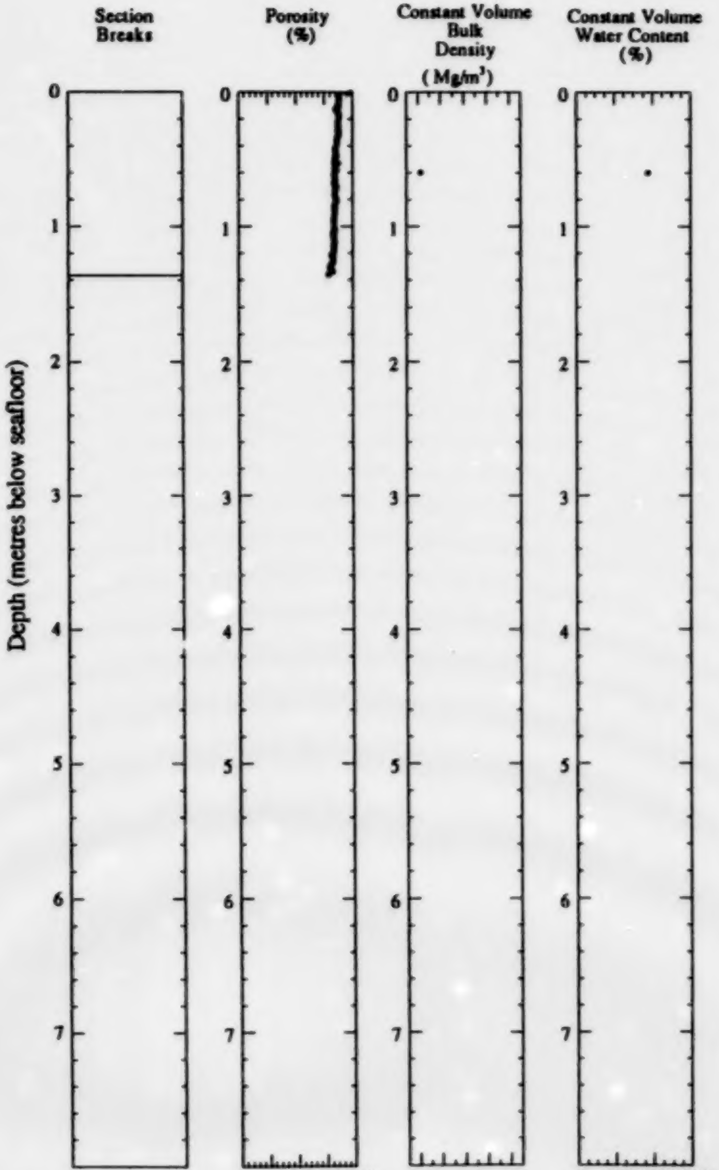

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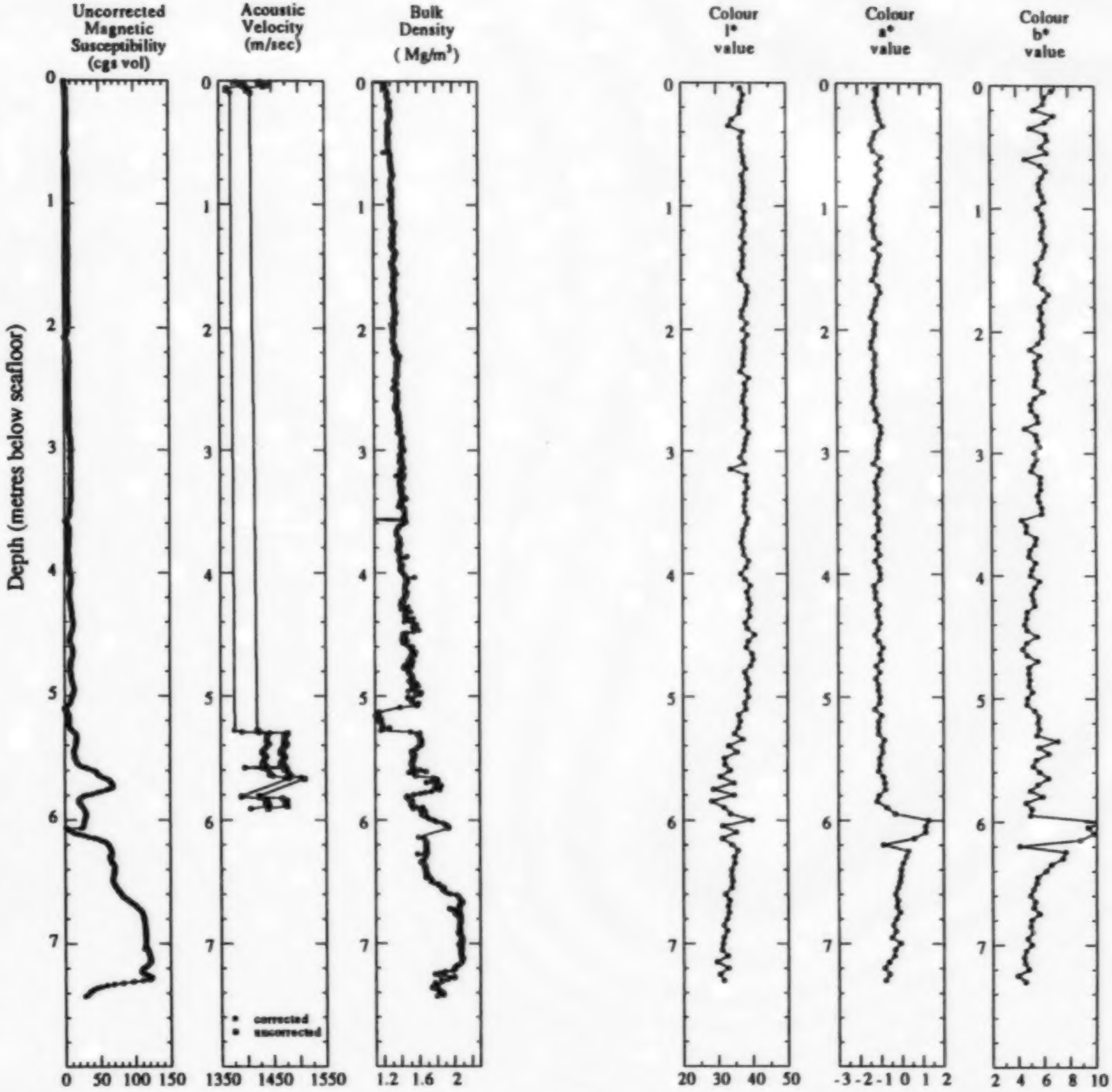

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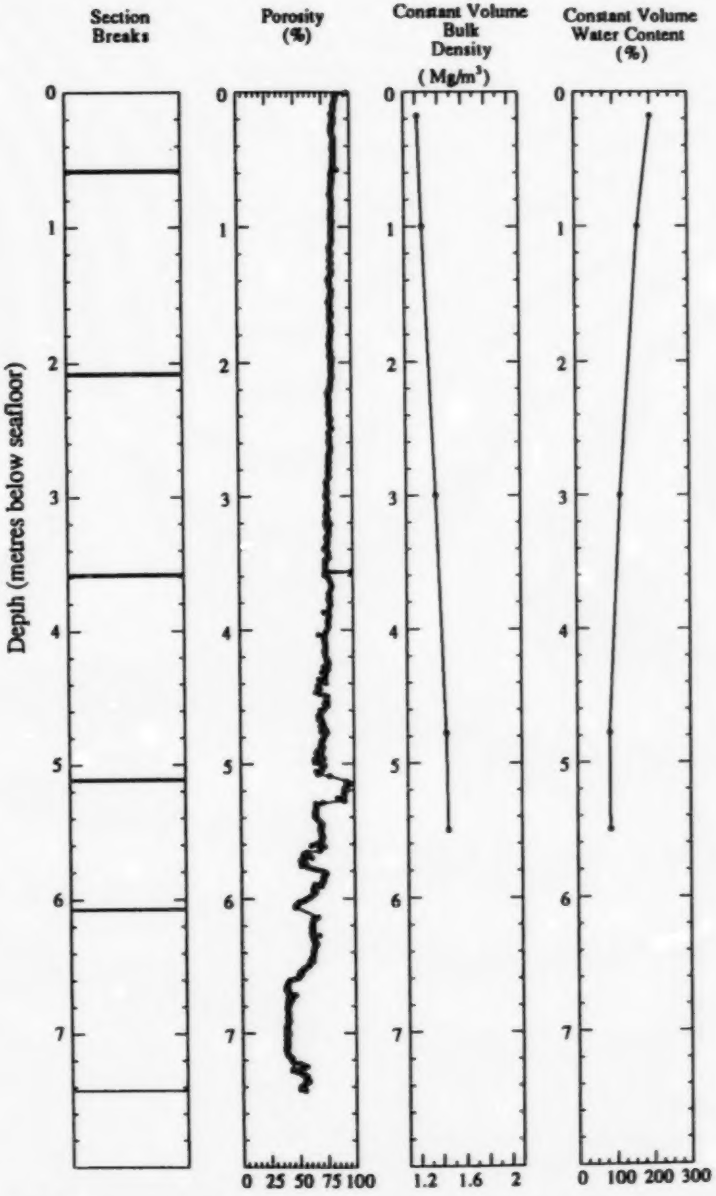
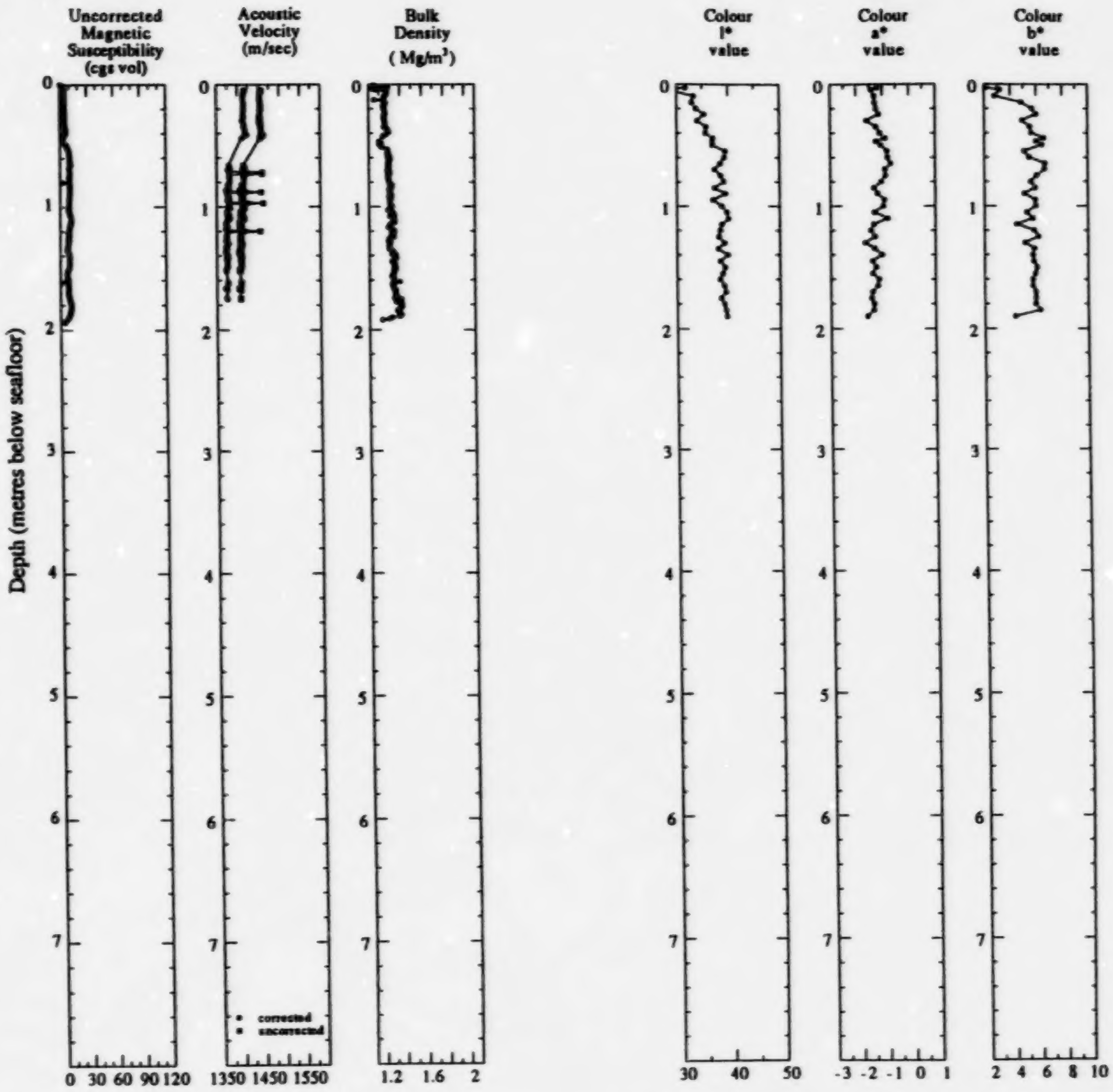


PART 2

96900 Lake Winnipeg 201 gravity core



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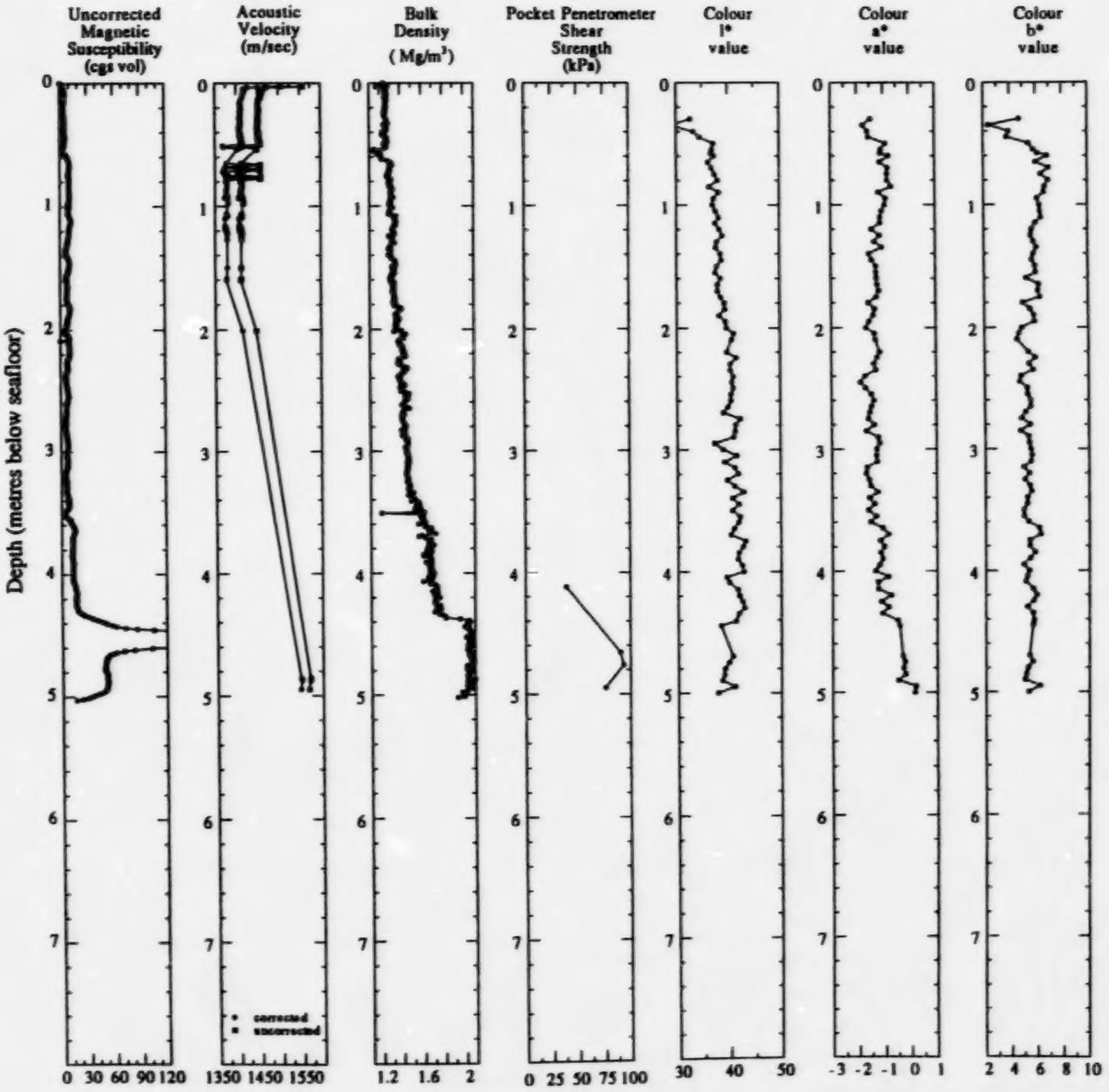

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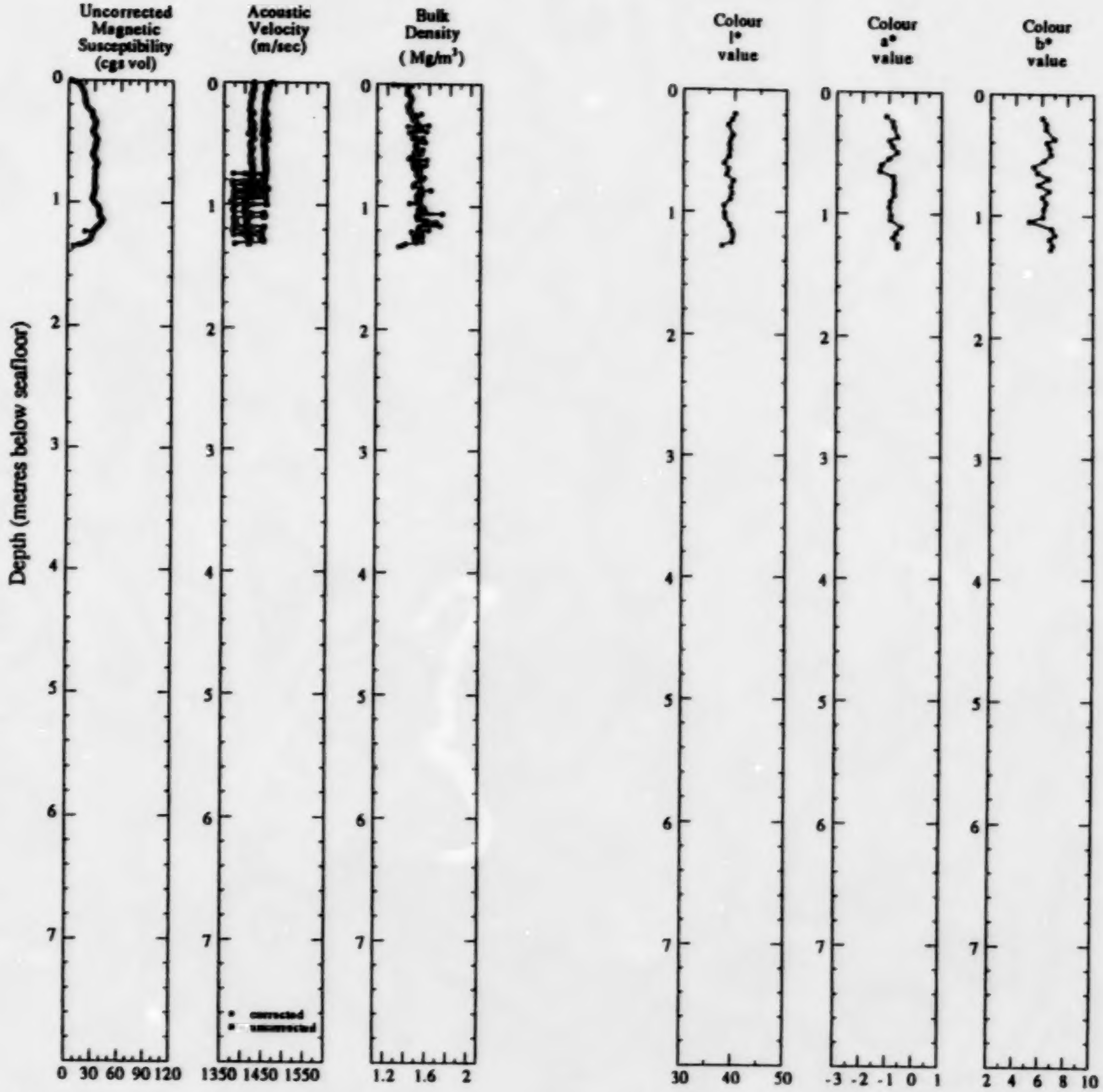

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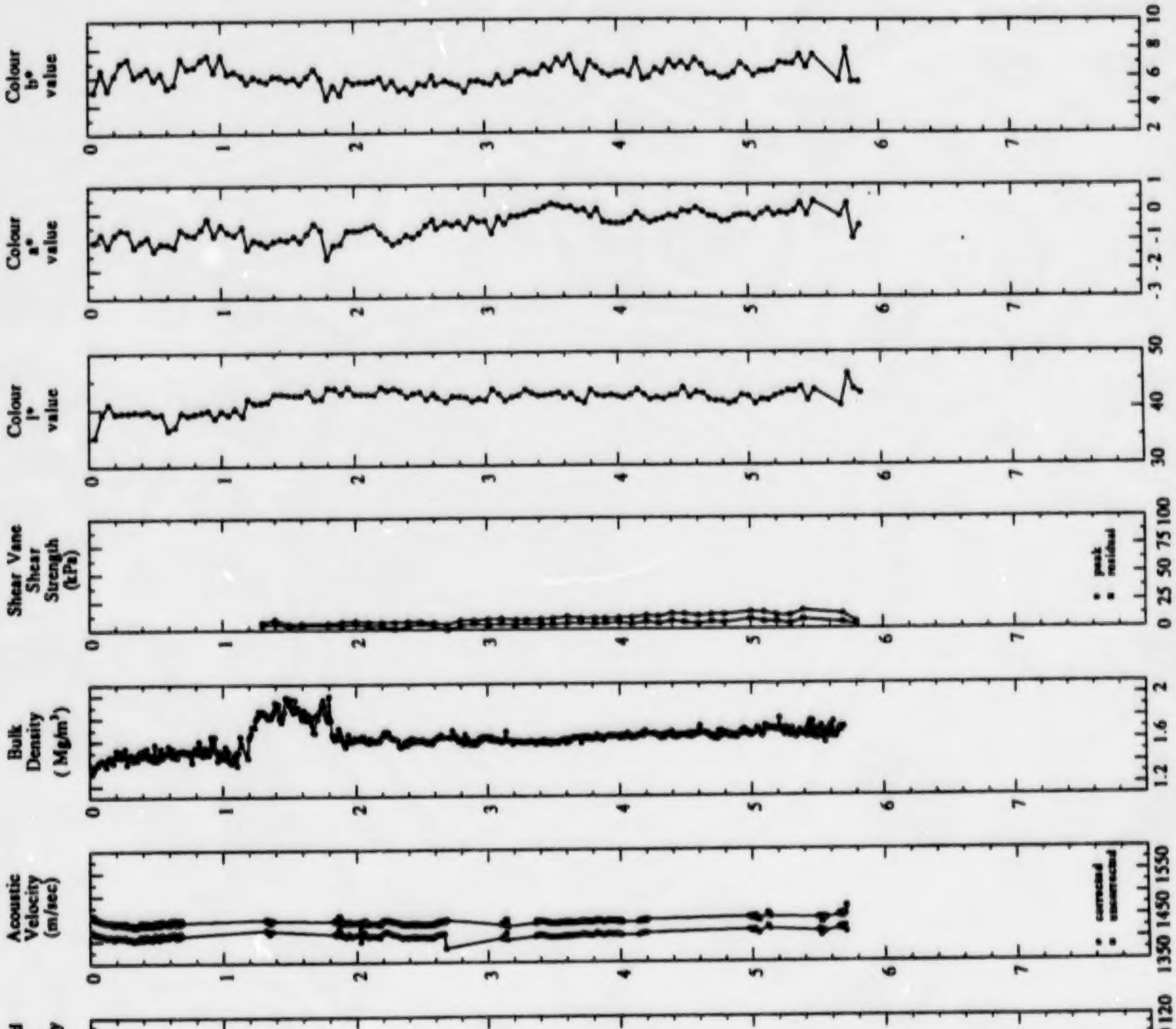

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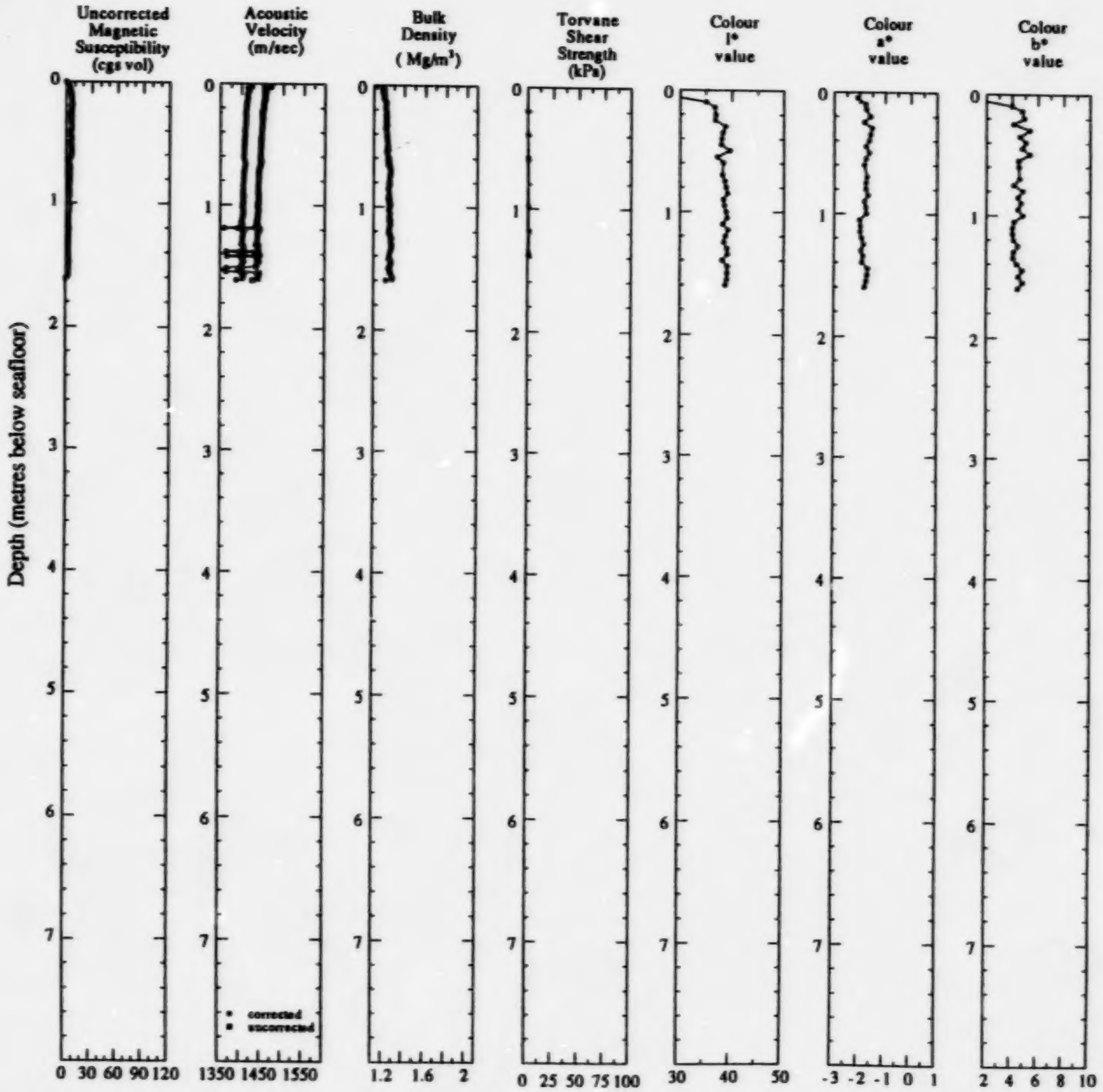

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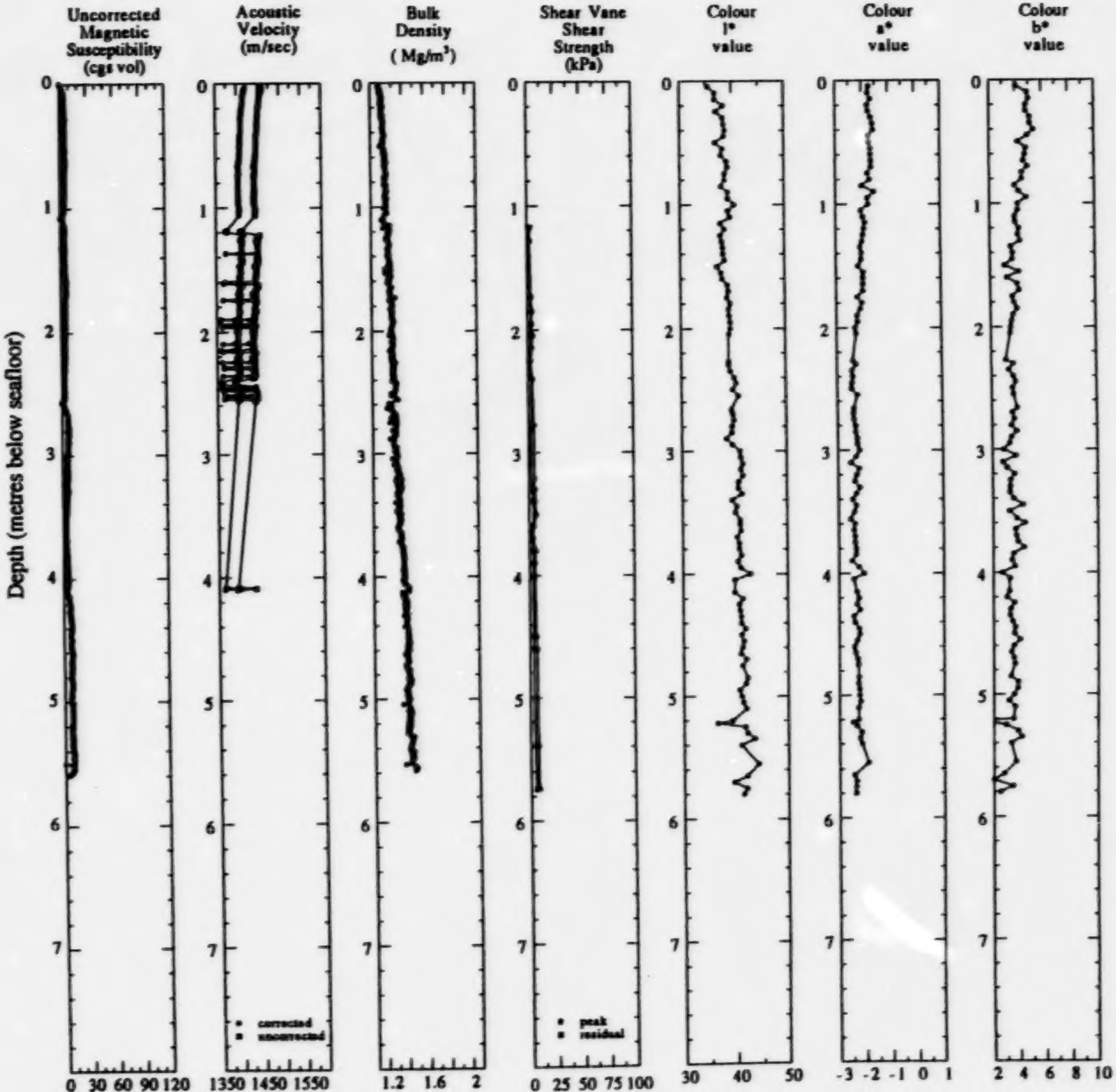

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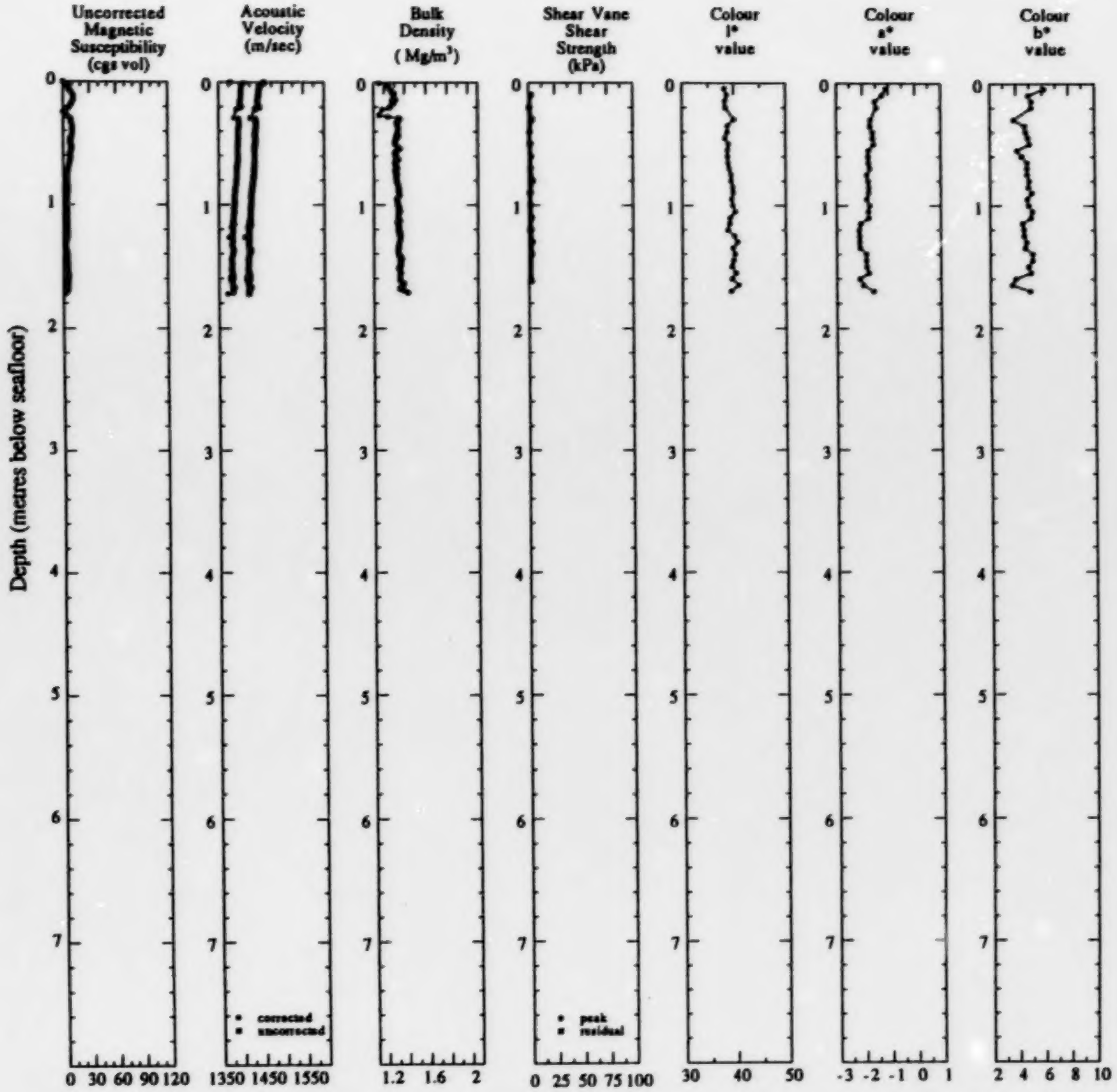

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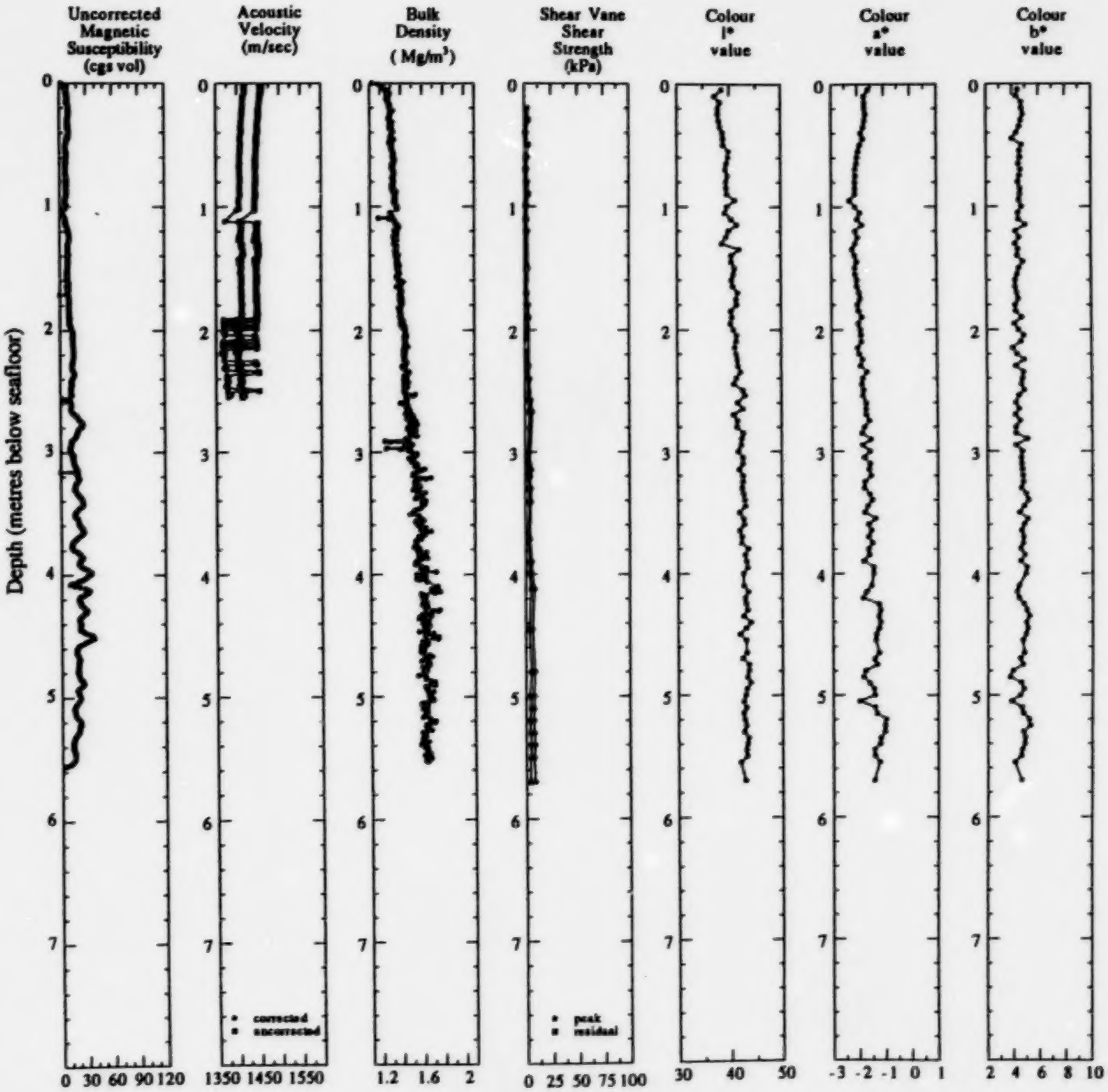

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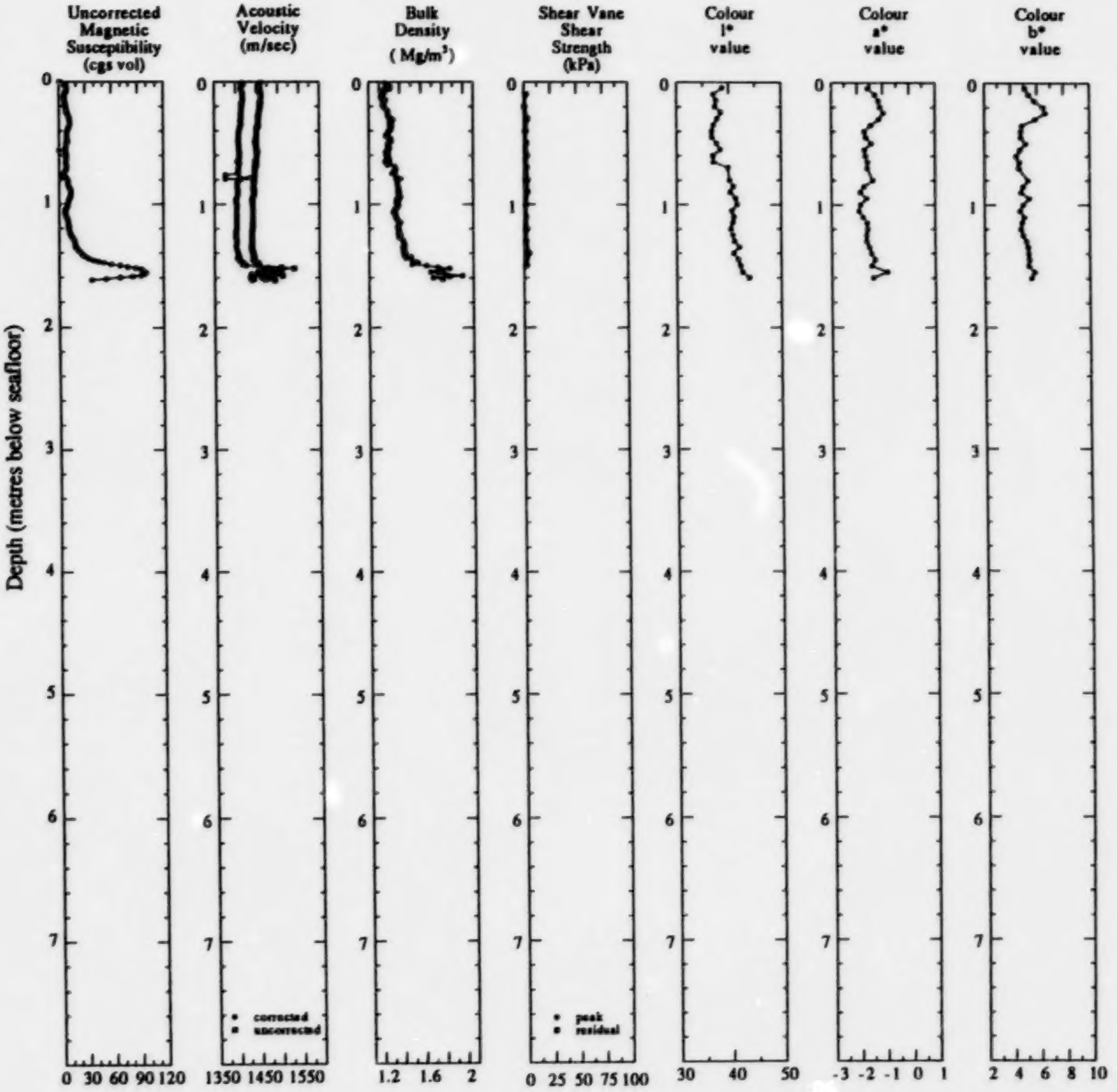

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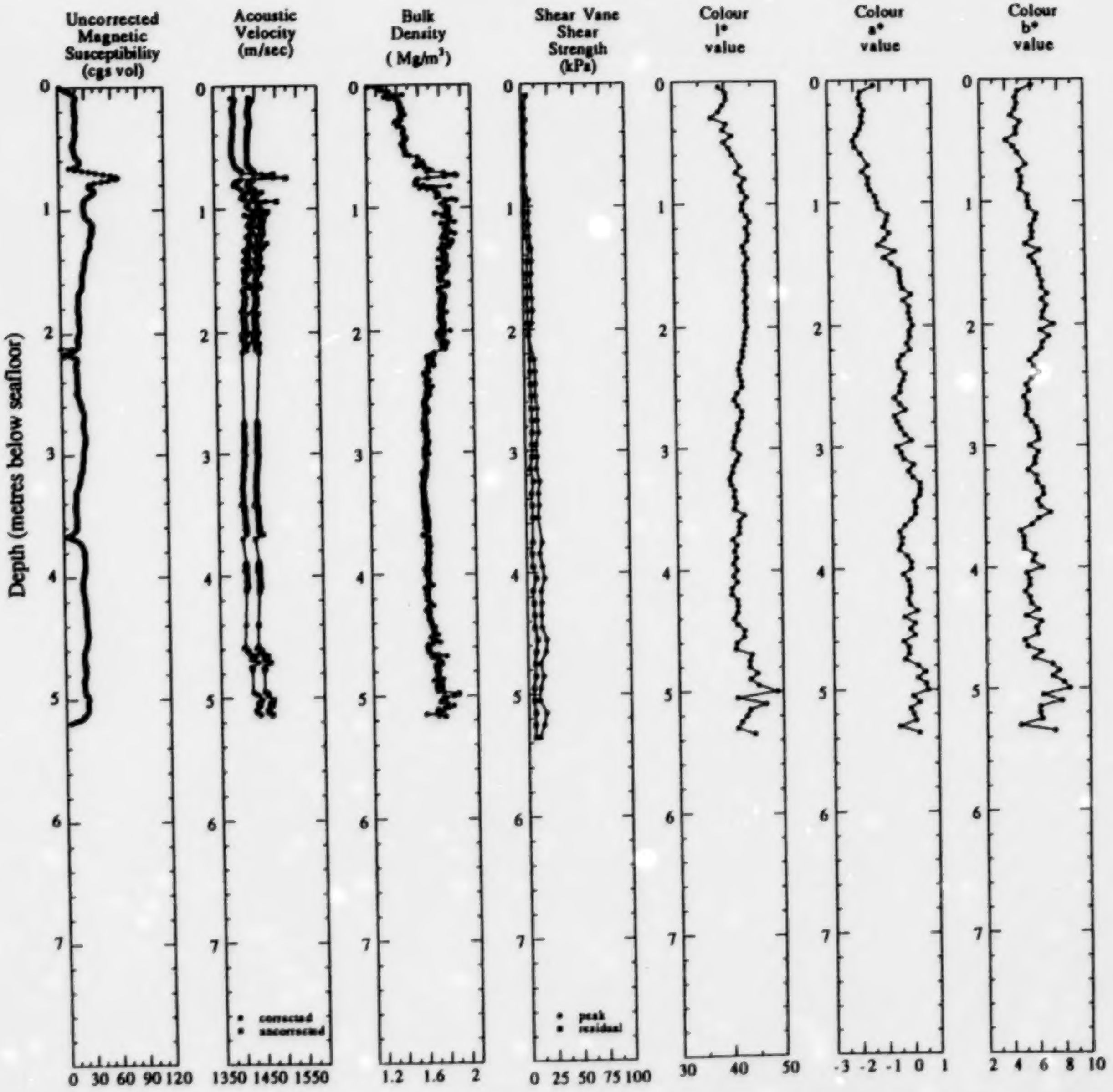

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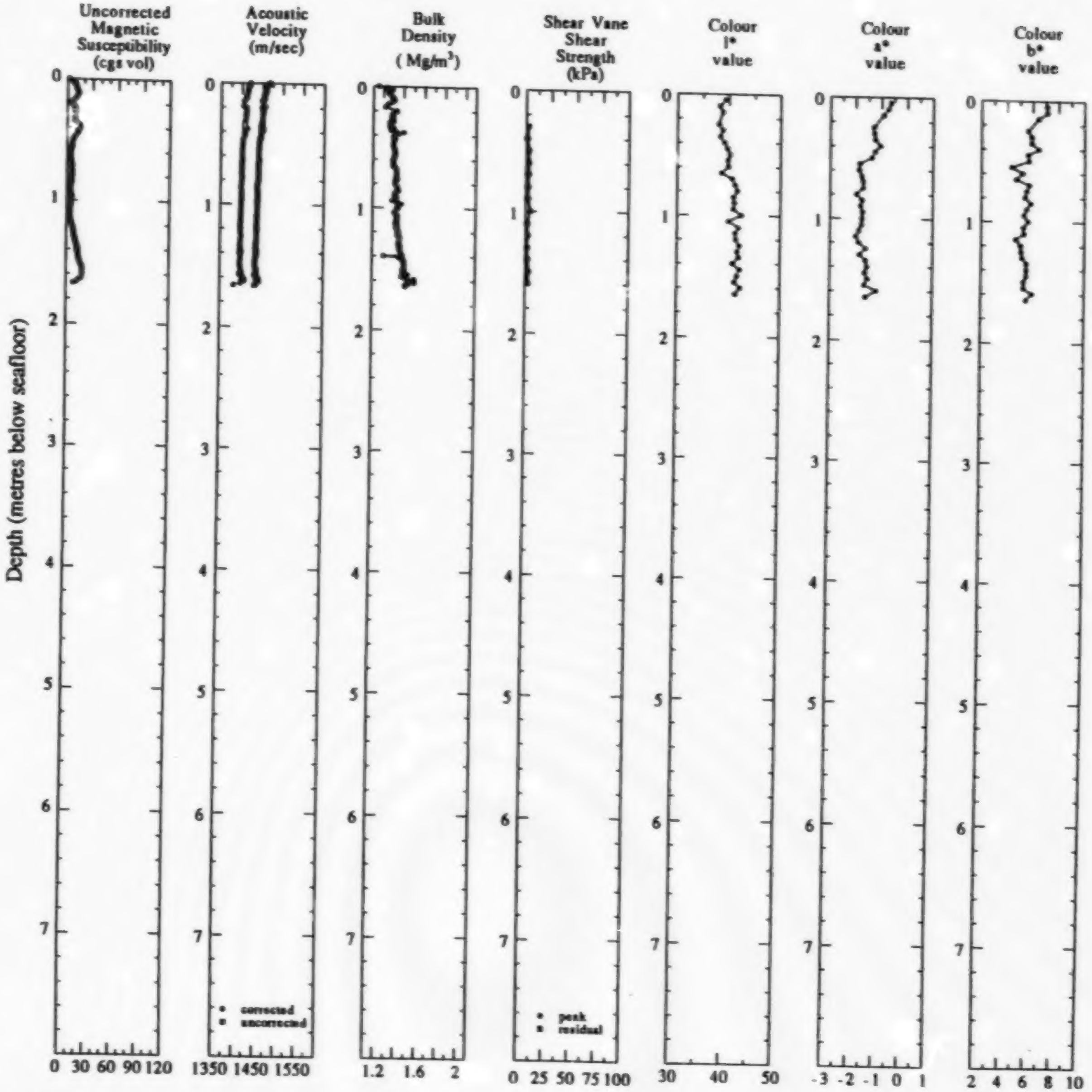

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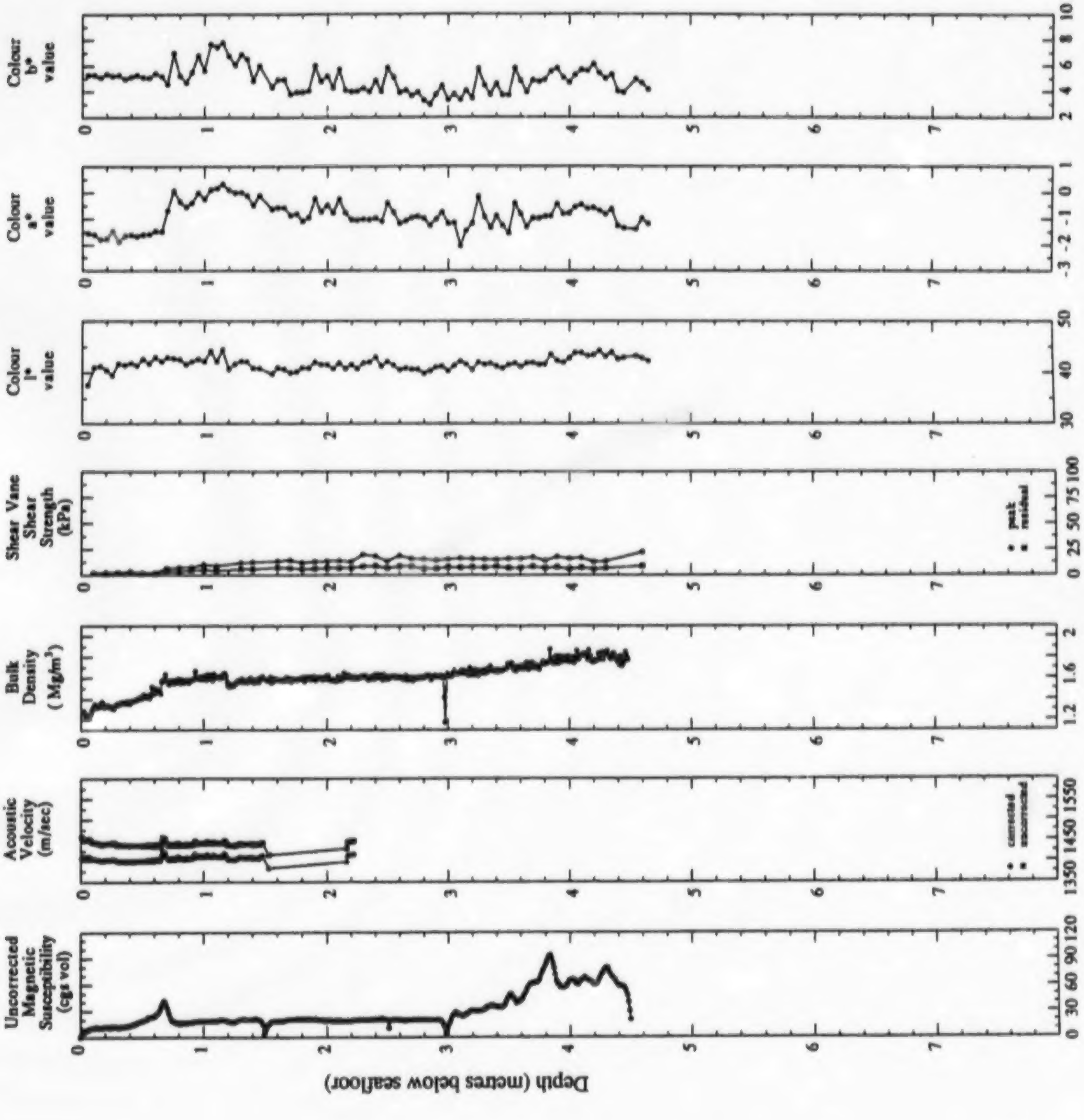

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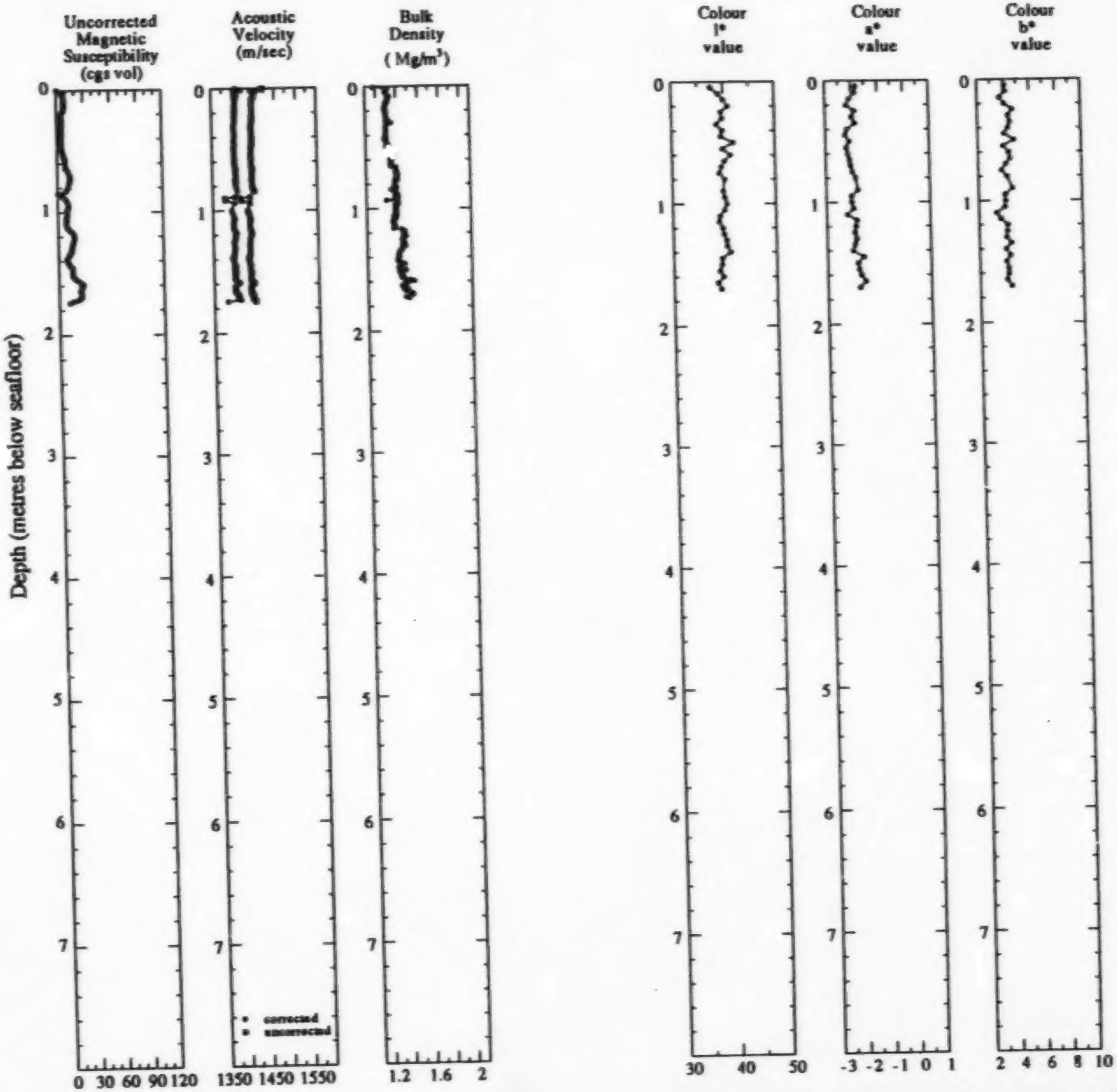

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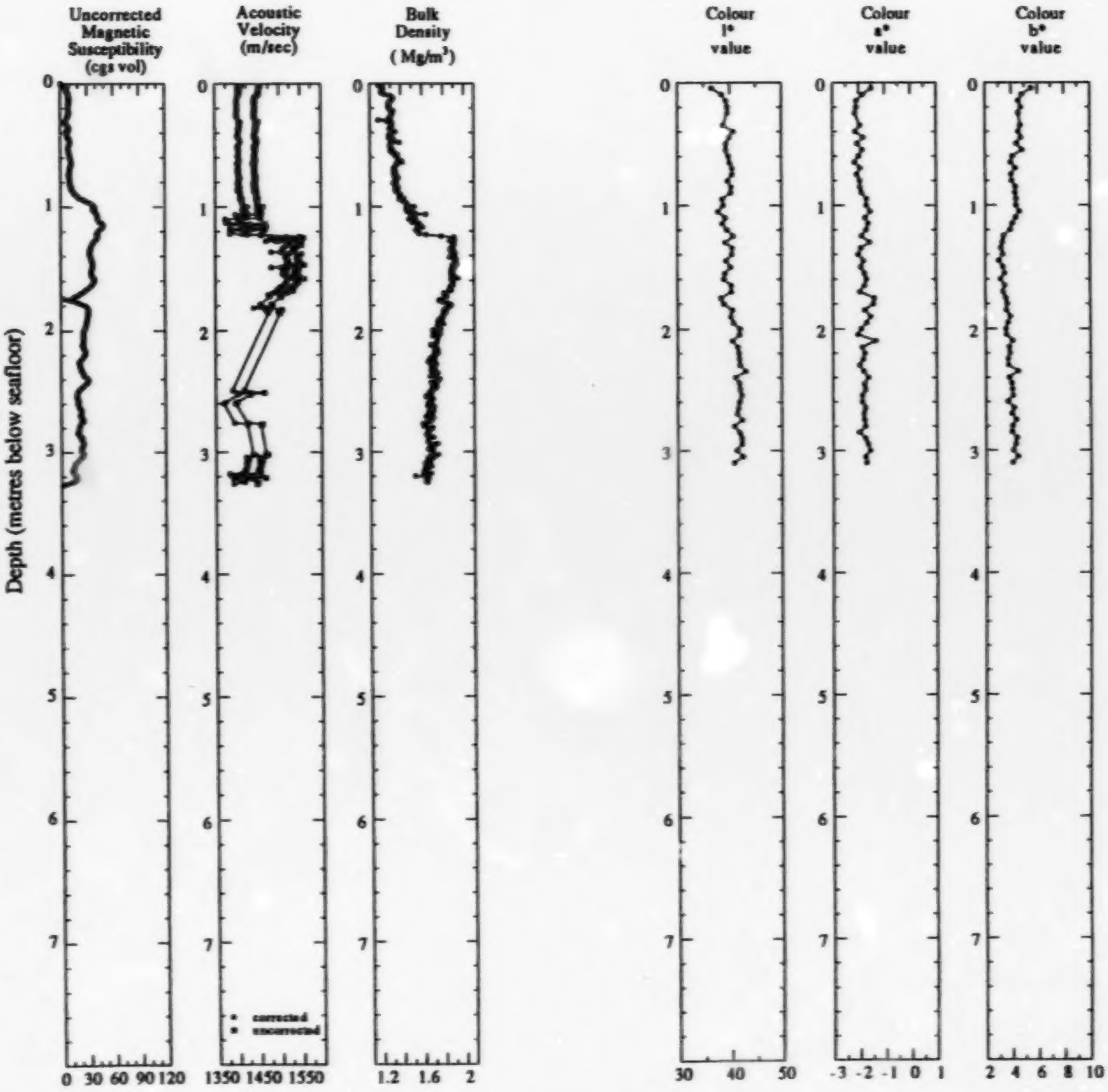

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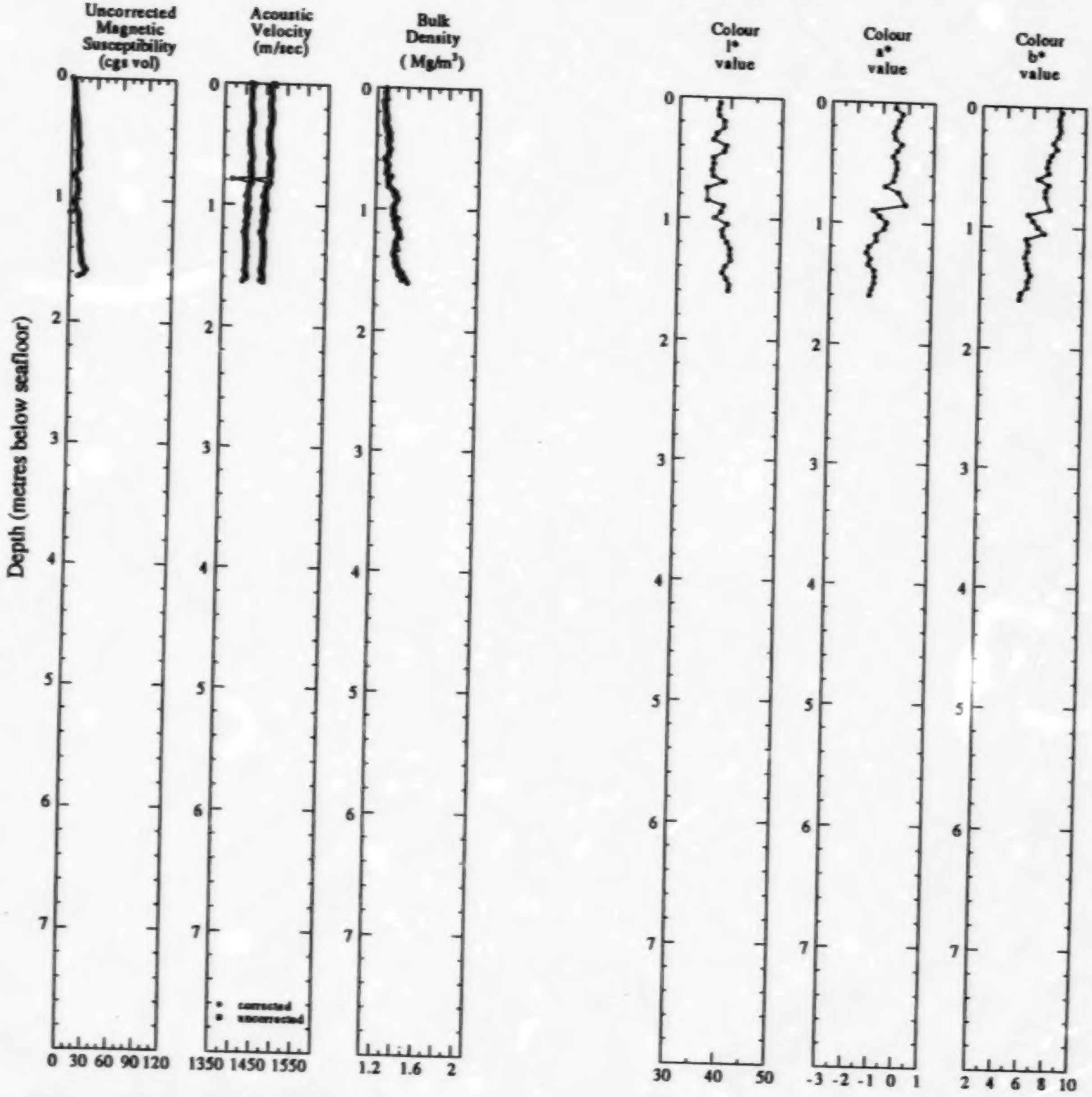

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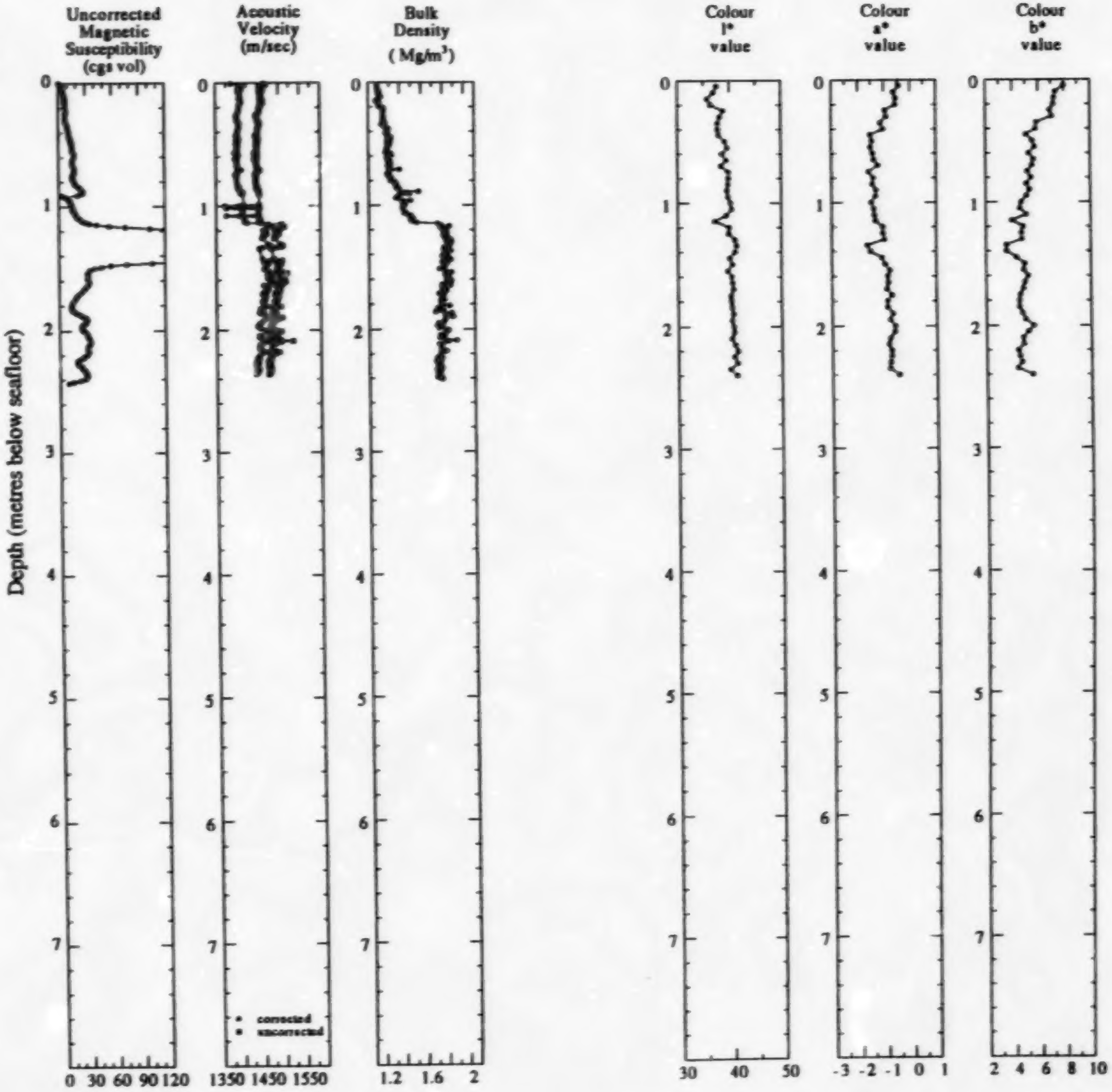

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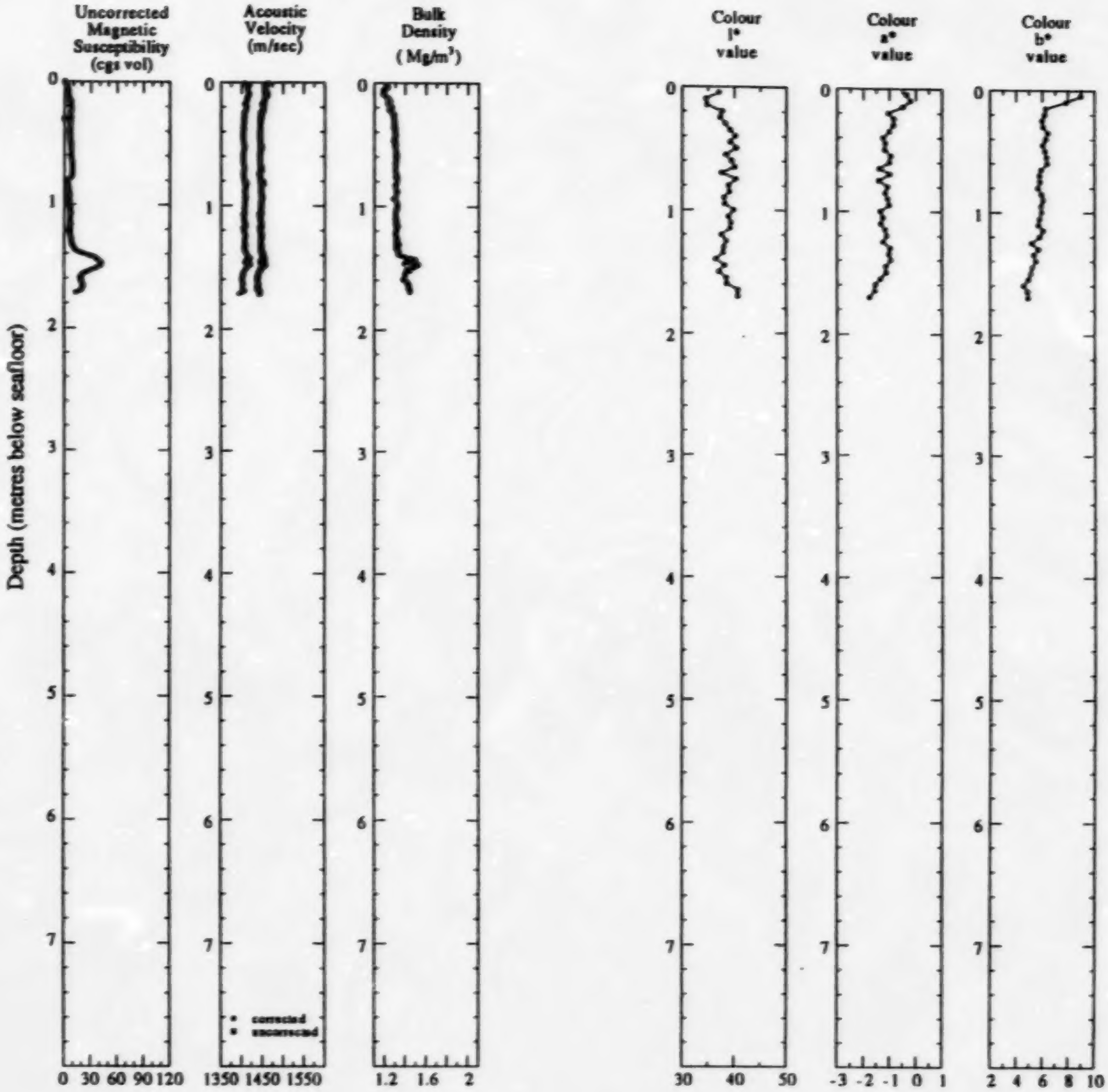

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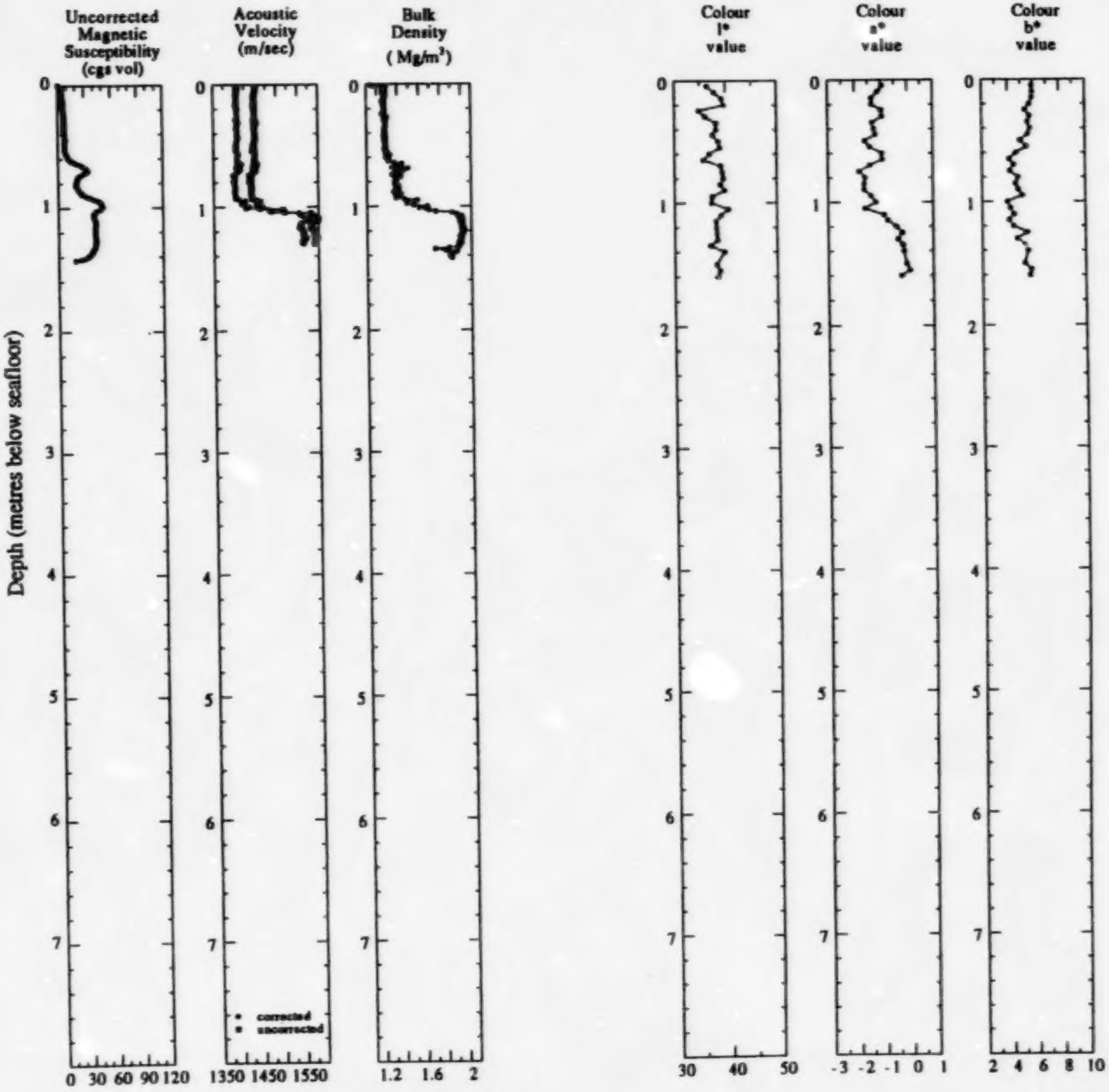

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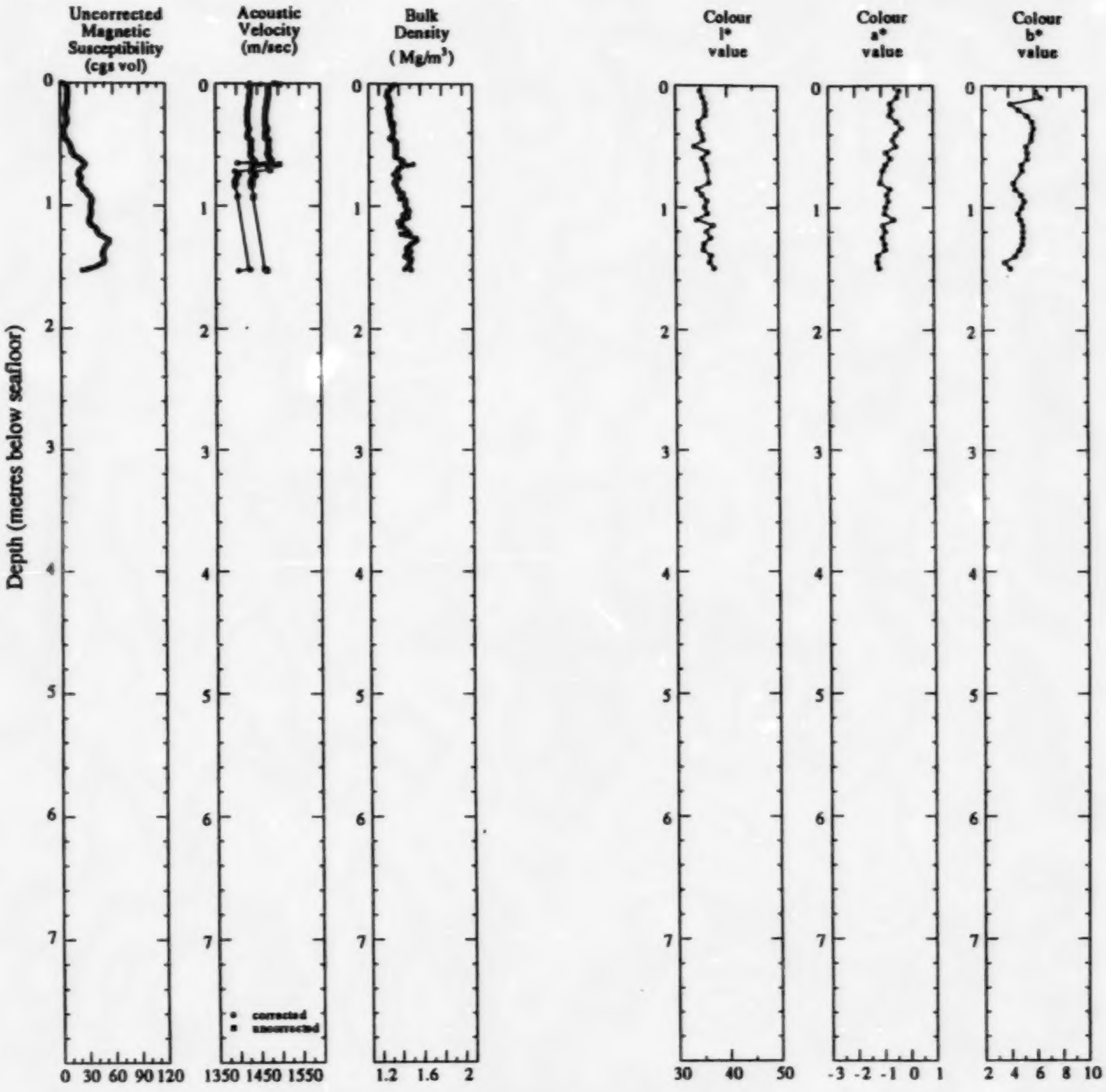

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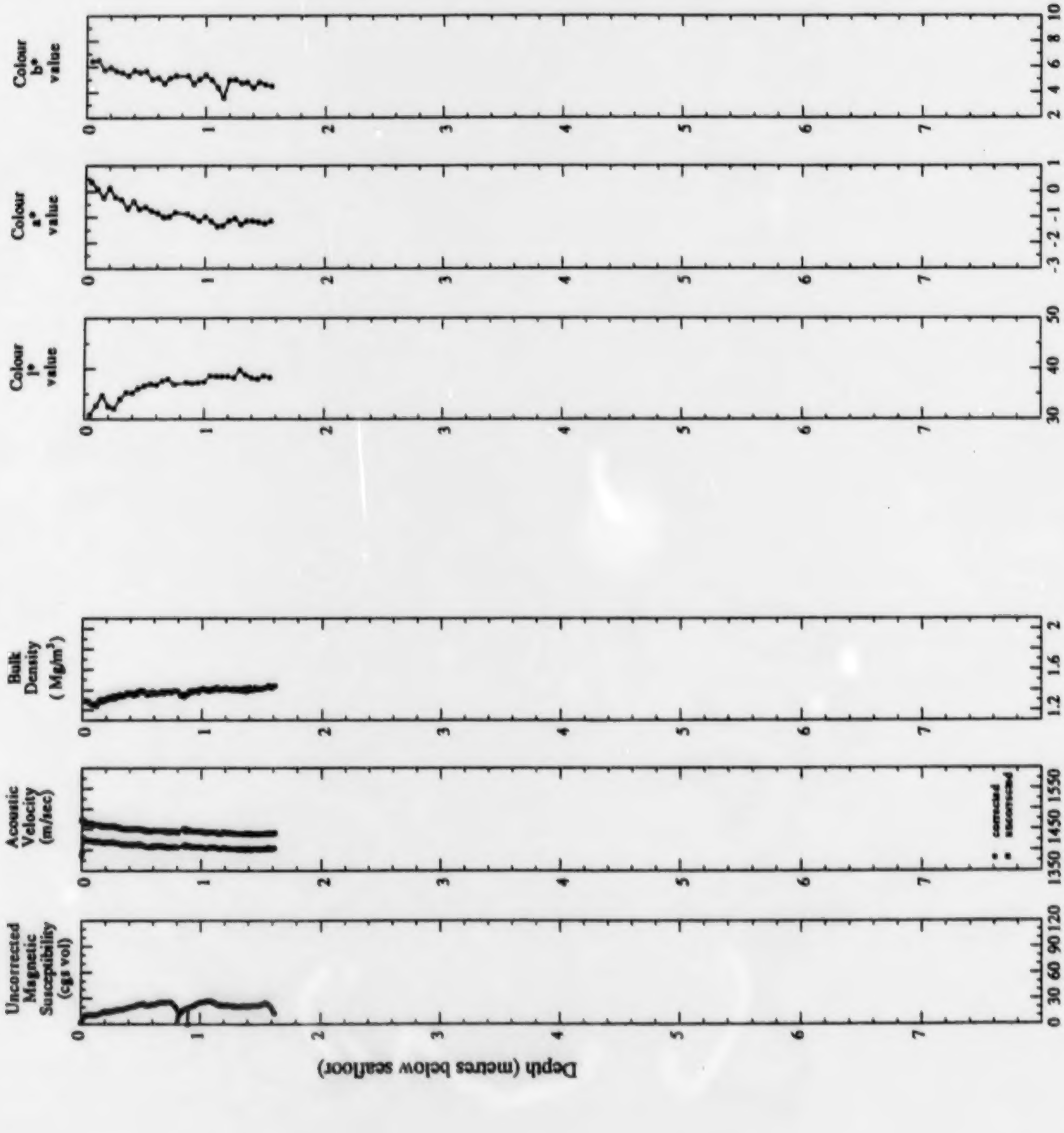

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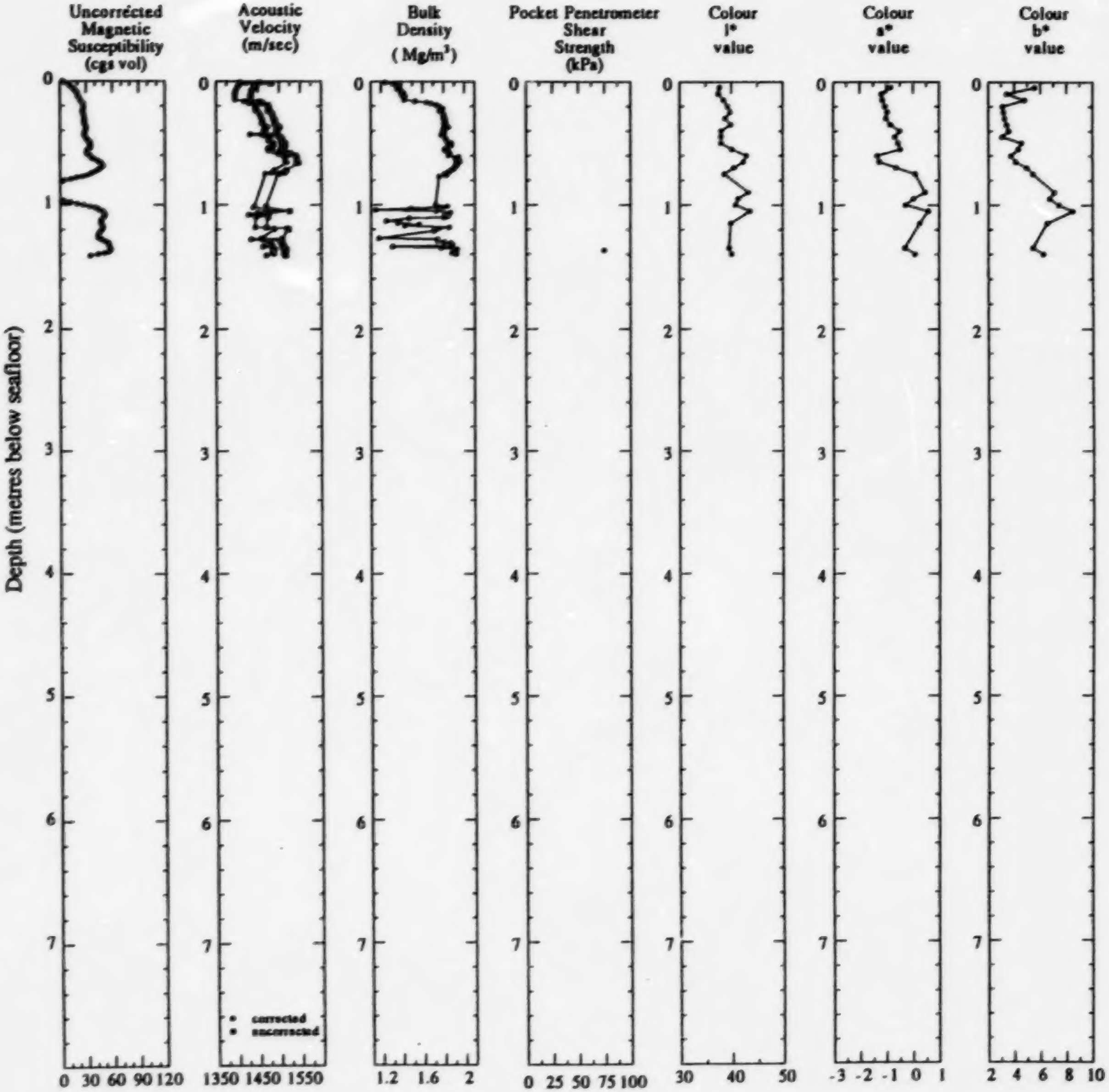

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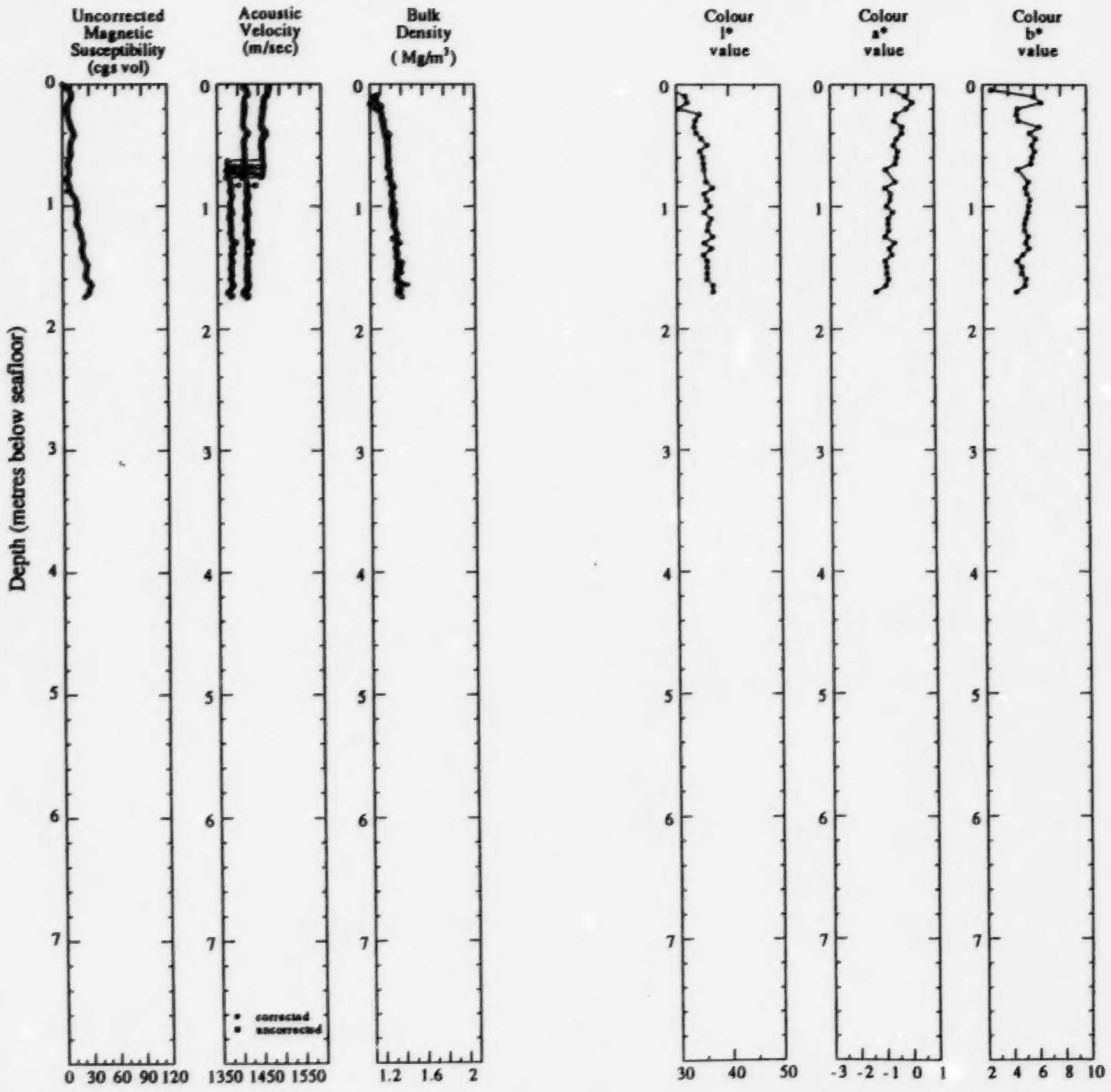

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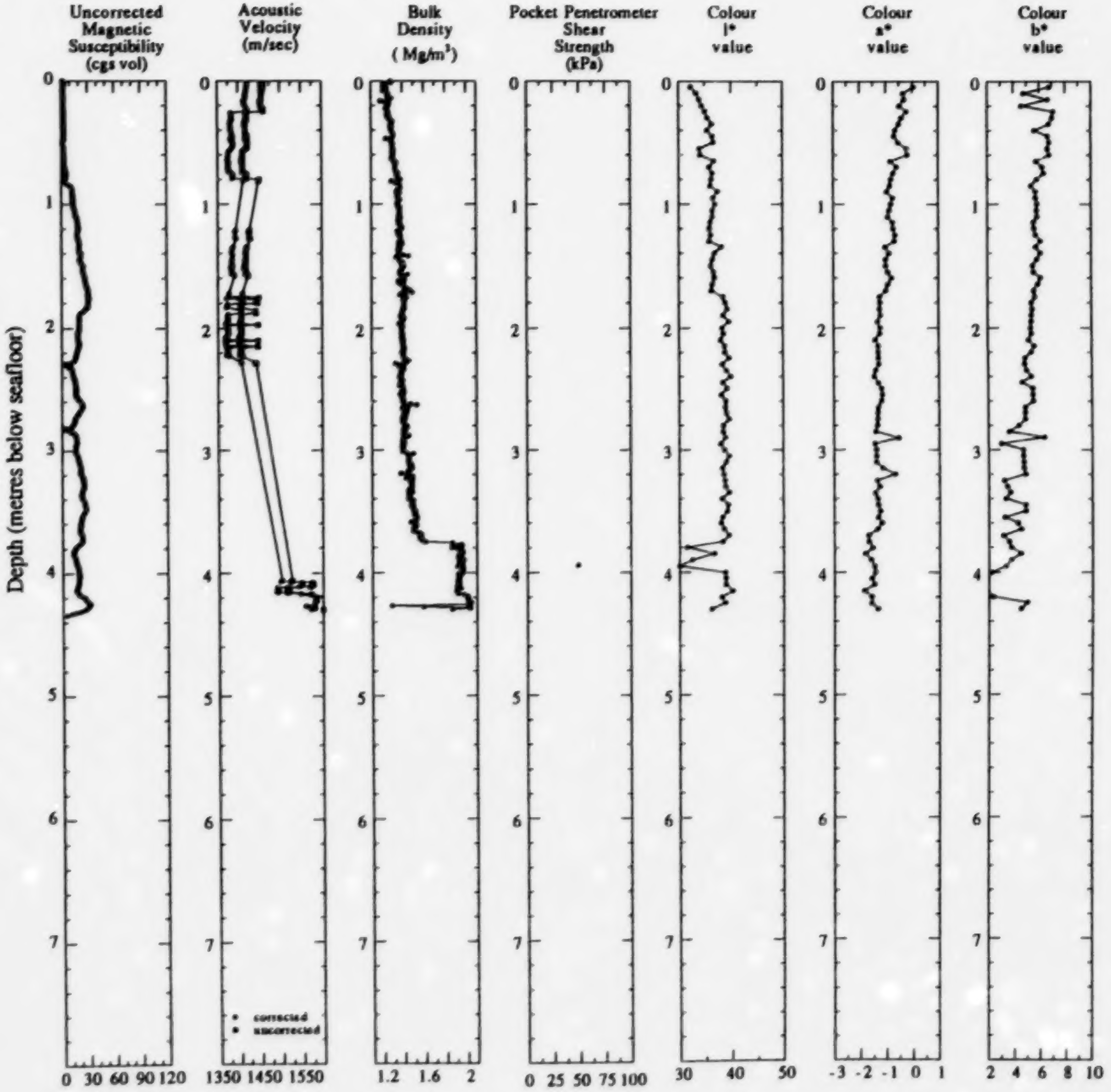

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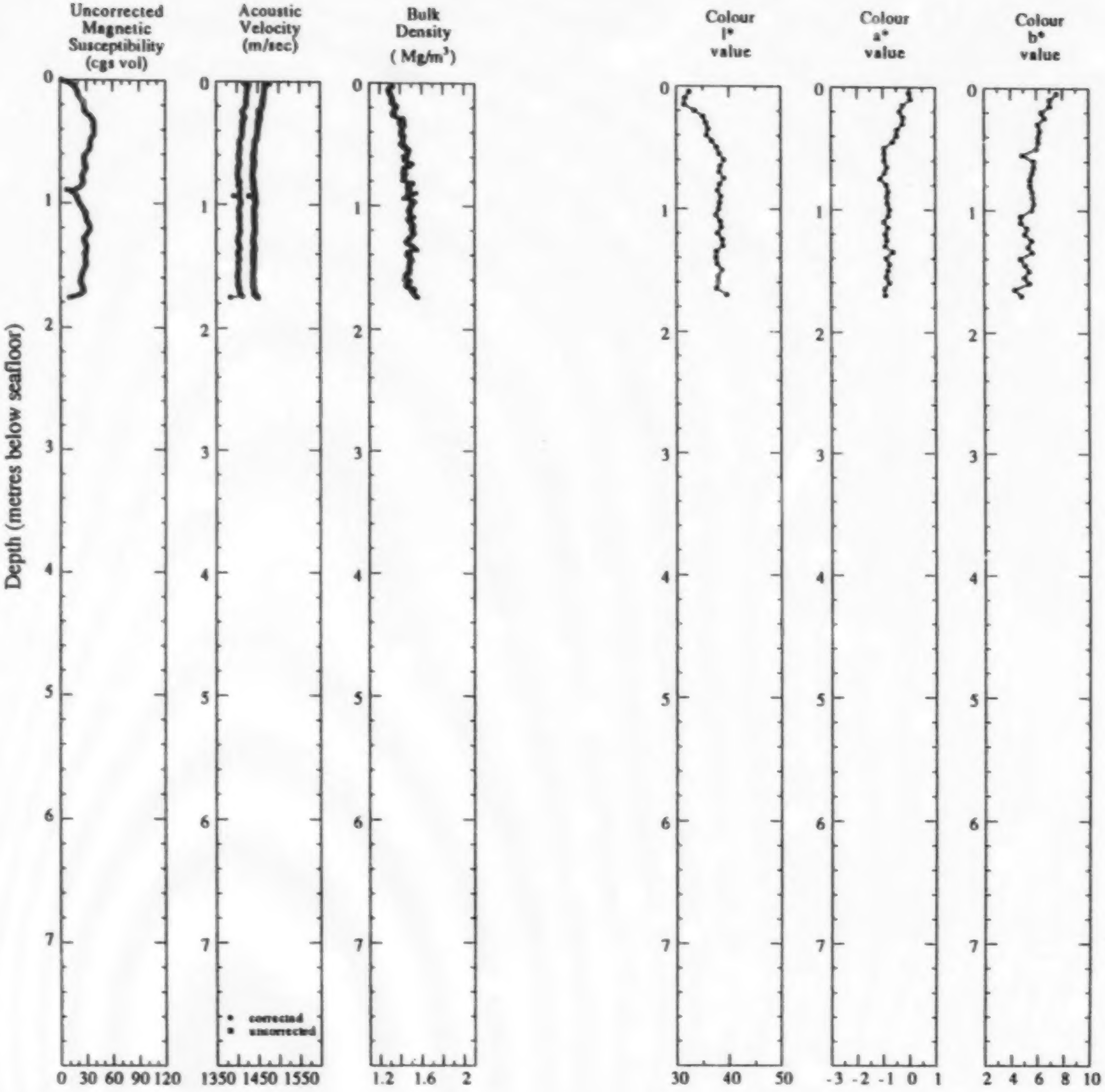

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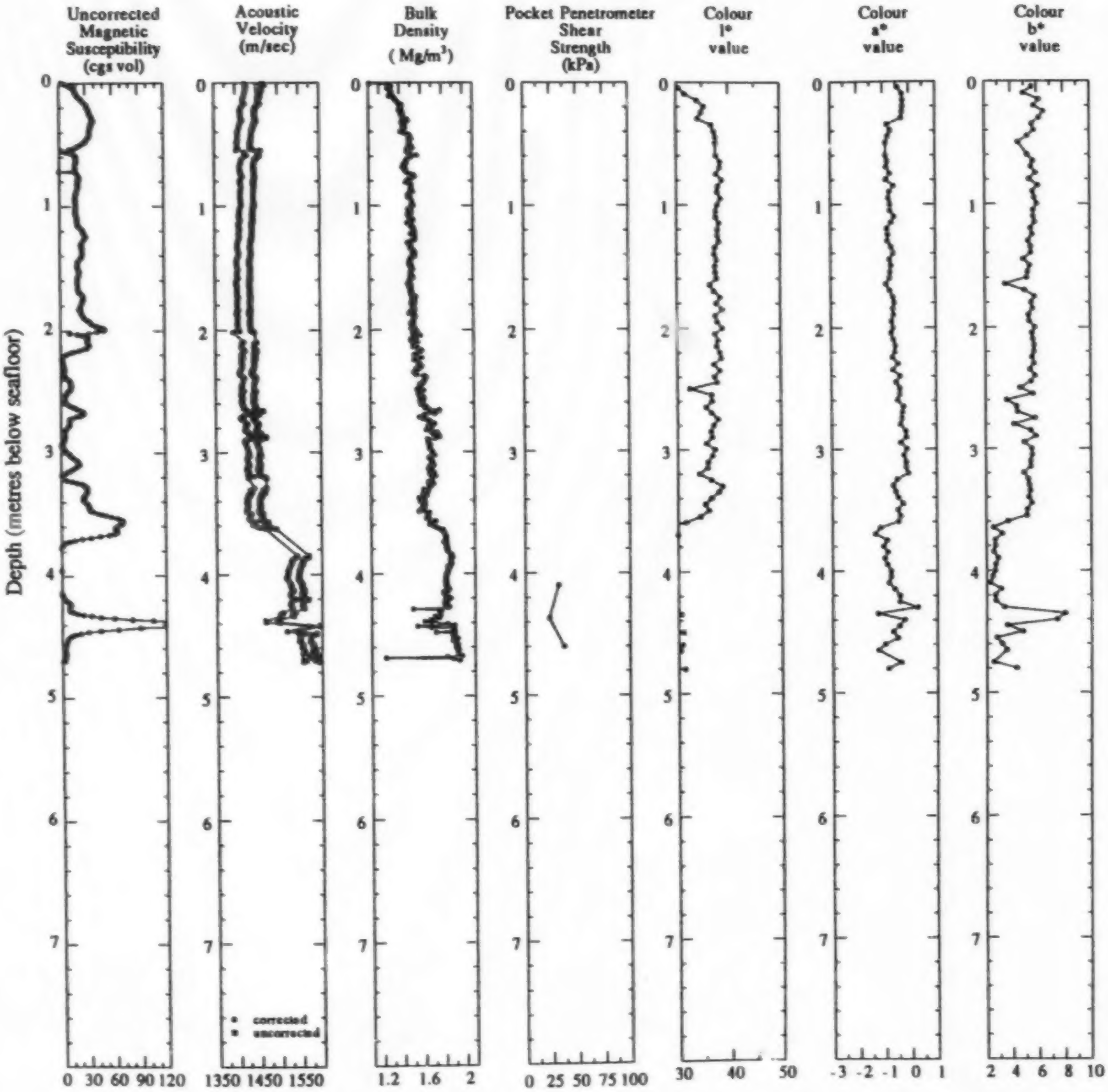

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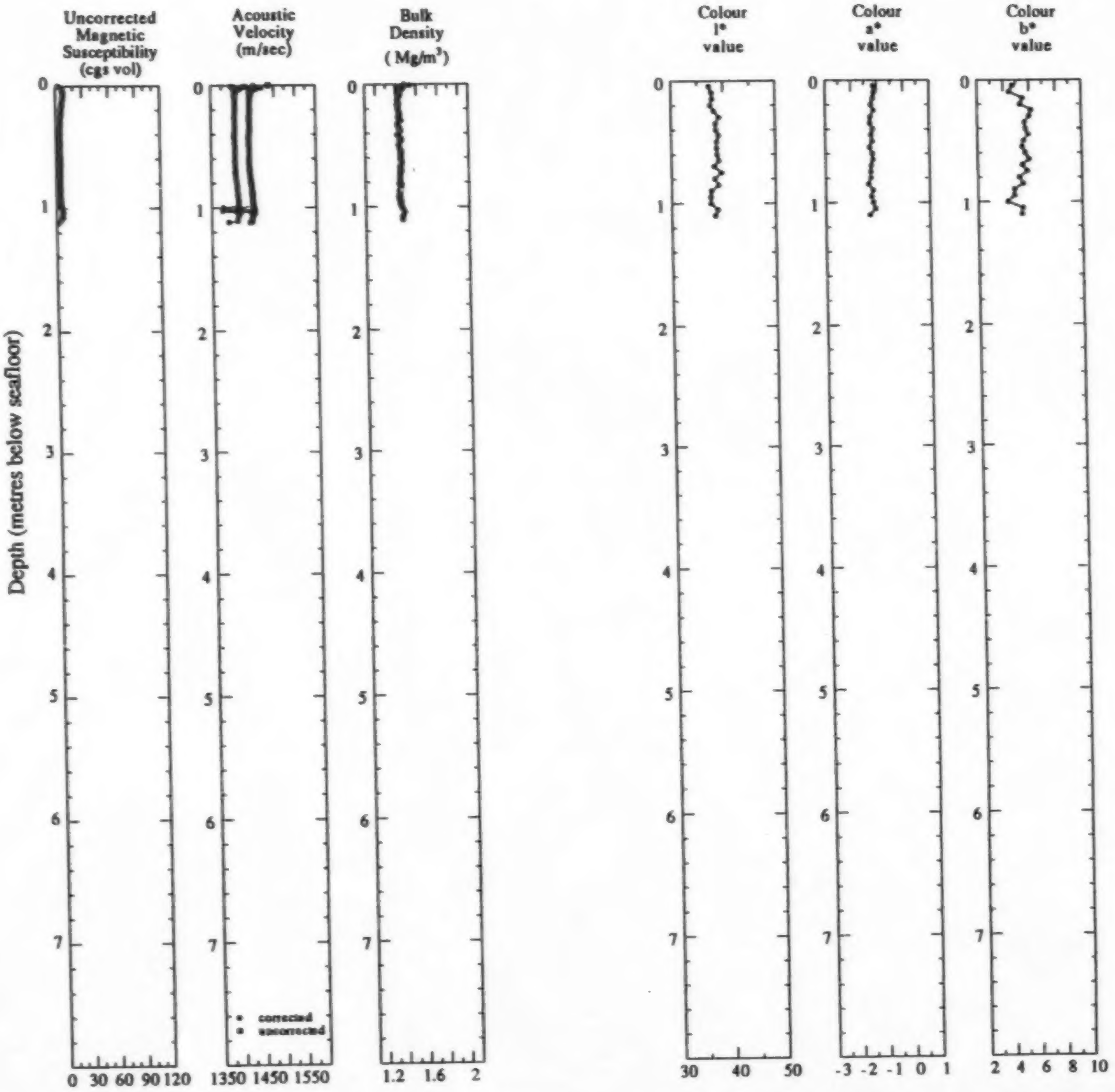
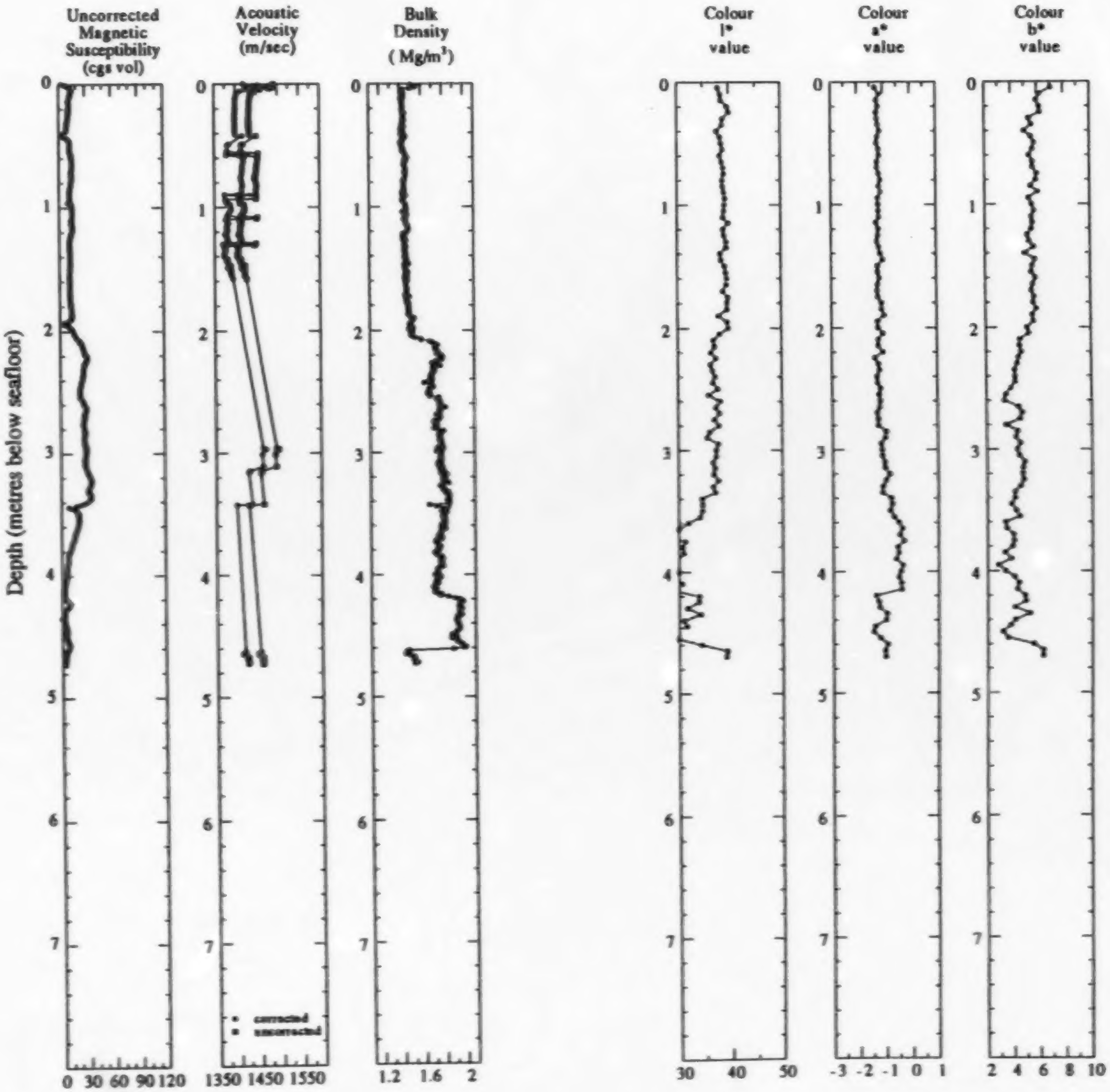
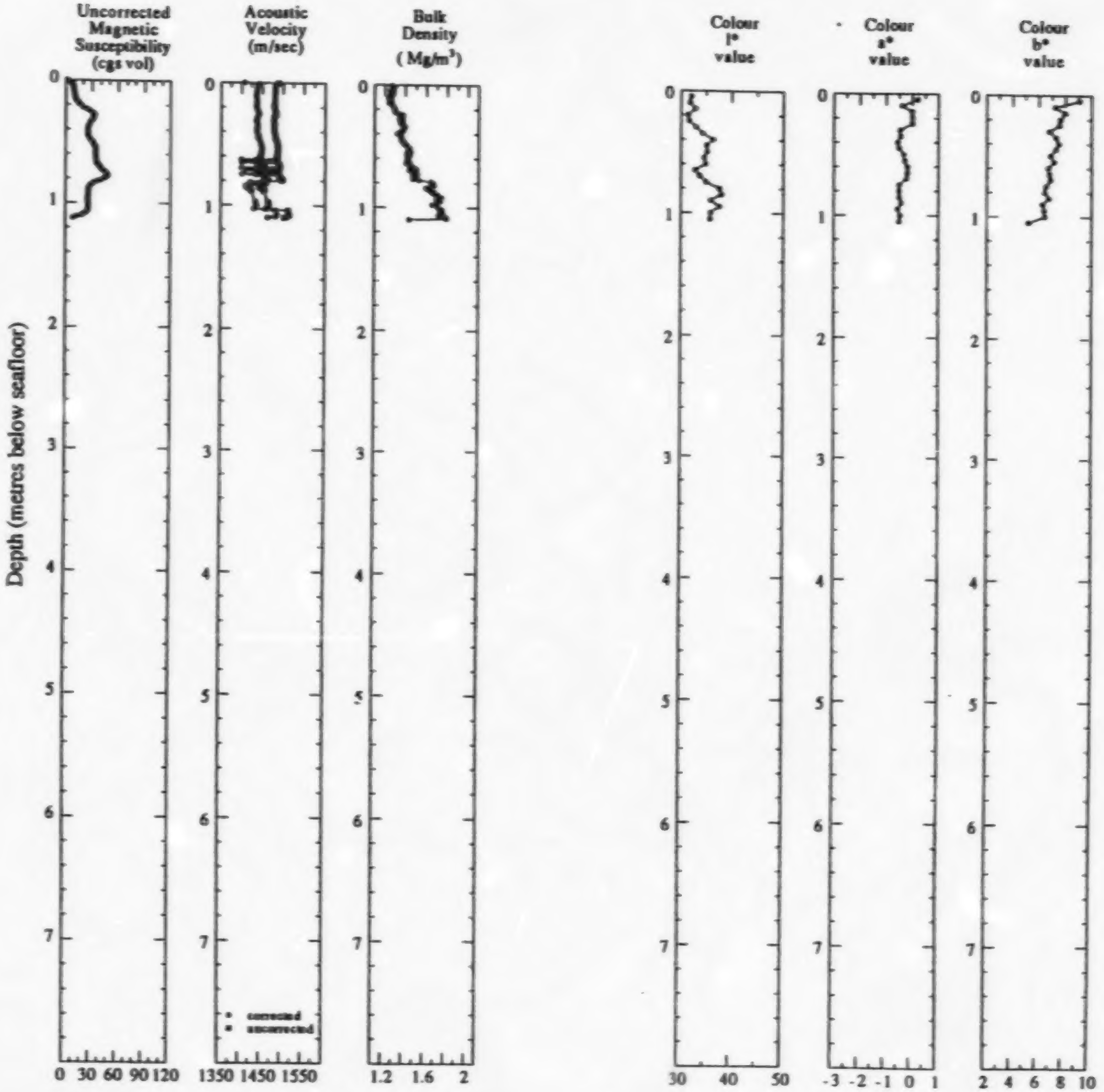


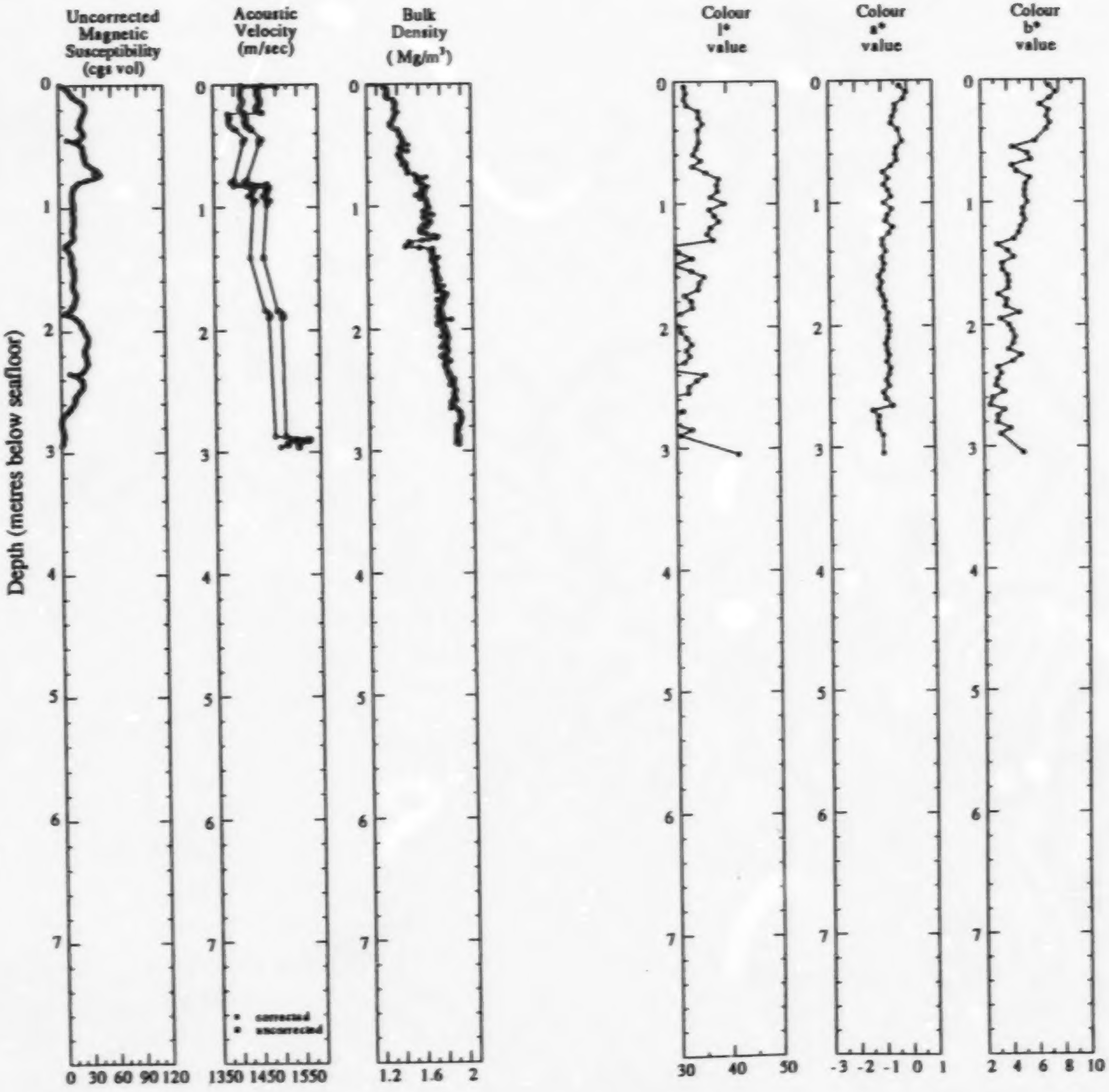
96900 Lake Winnipeg 216 piston core



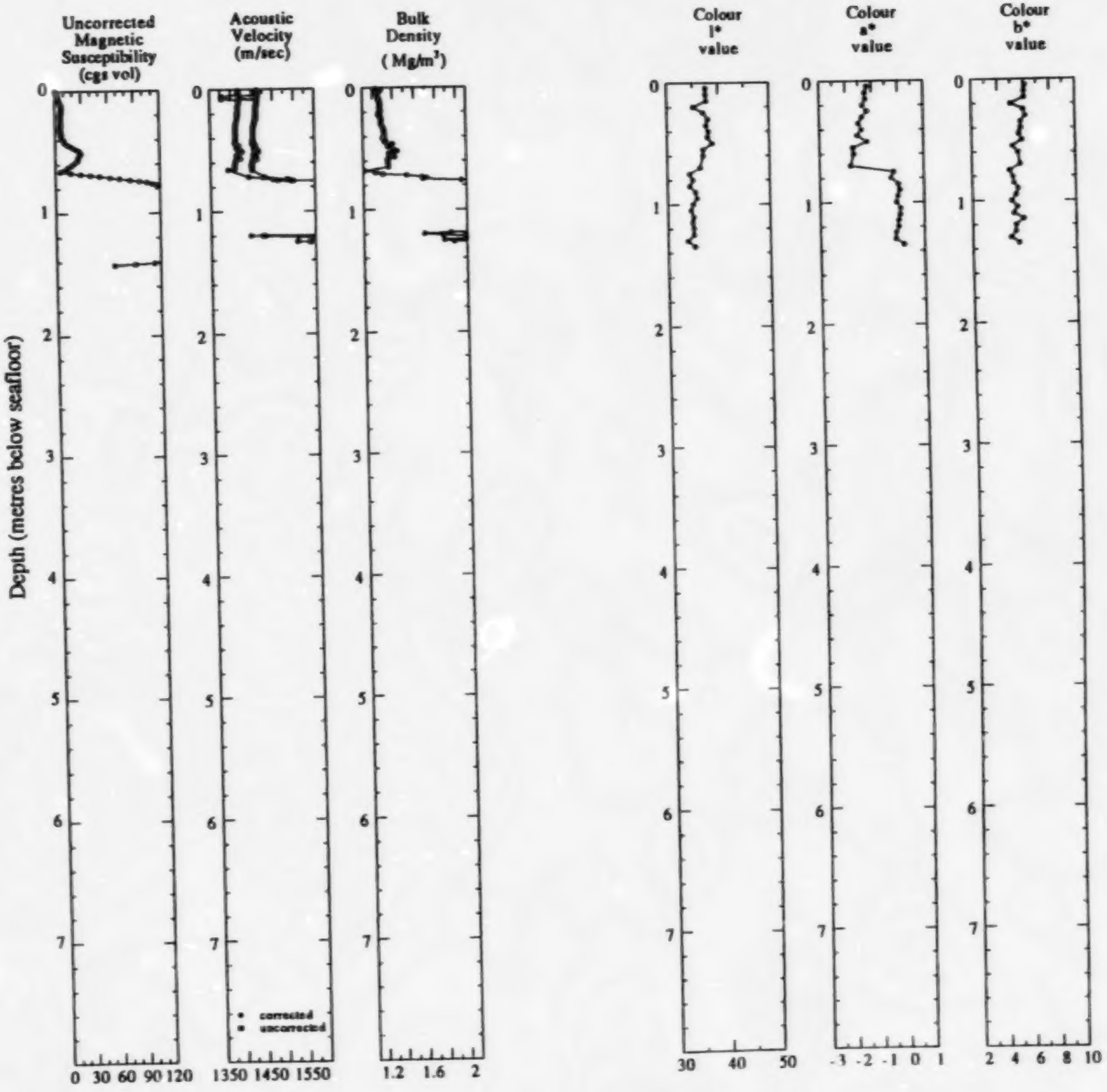
96900 Lake Winnipeg 217 gravity core



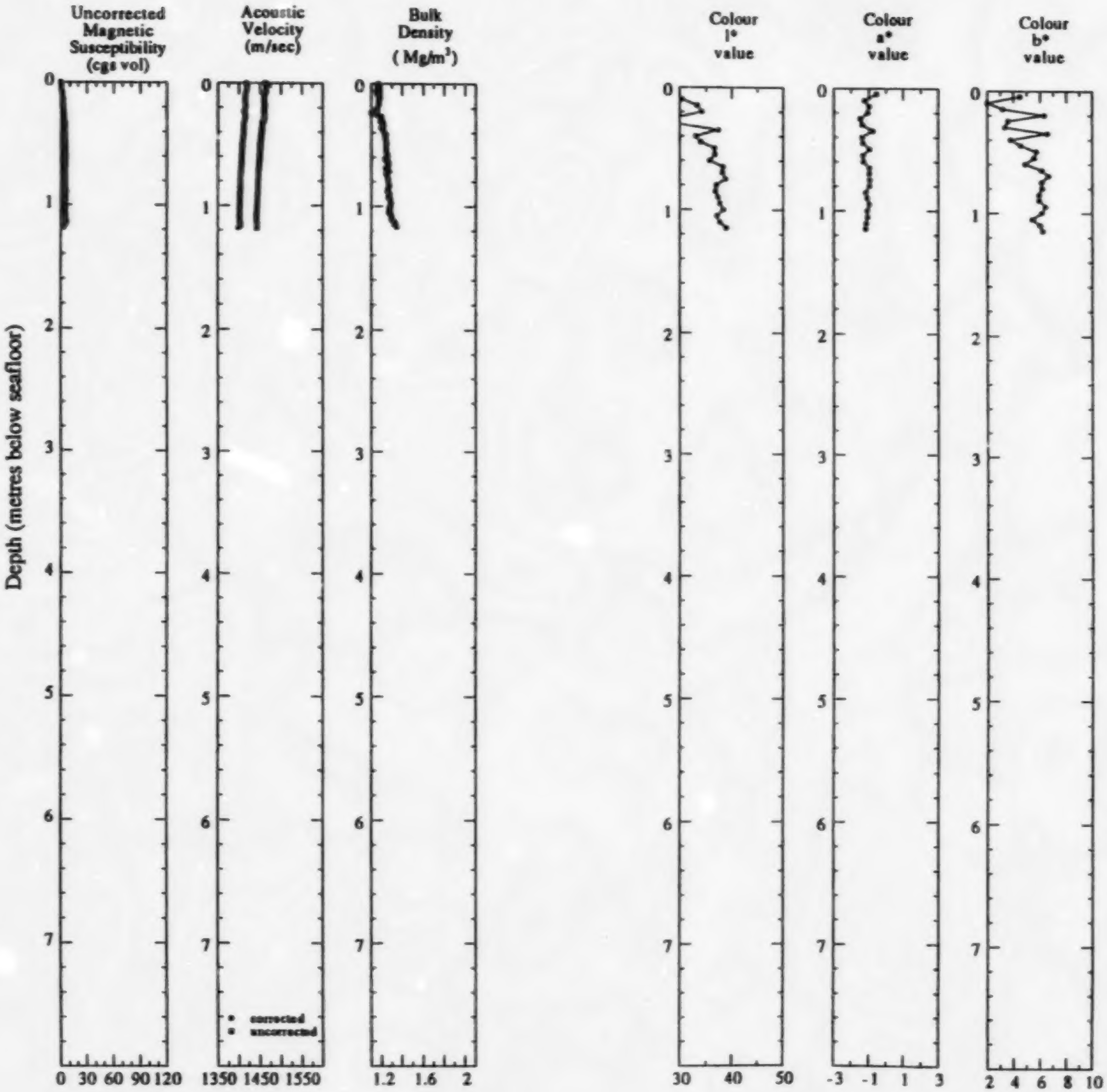
96900 Lake Winnipeg 217 piston core



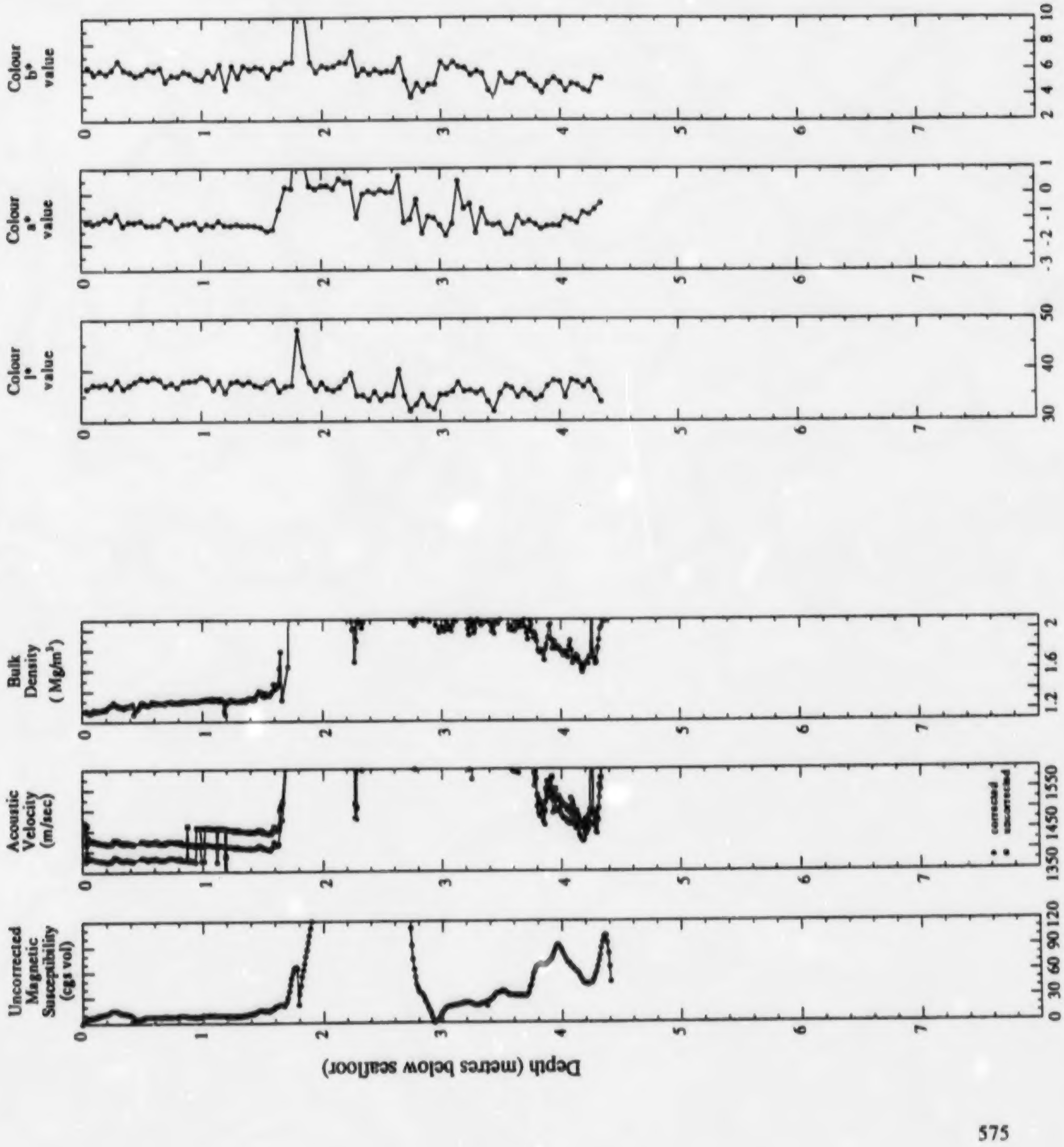
96900 Lake Winnipeg 218 piston core



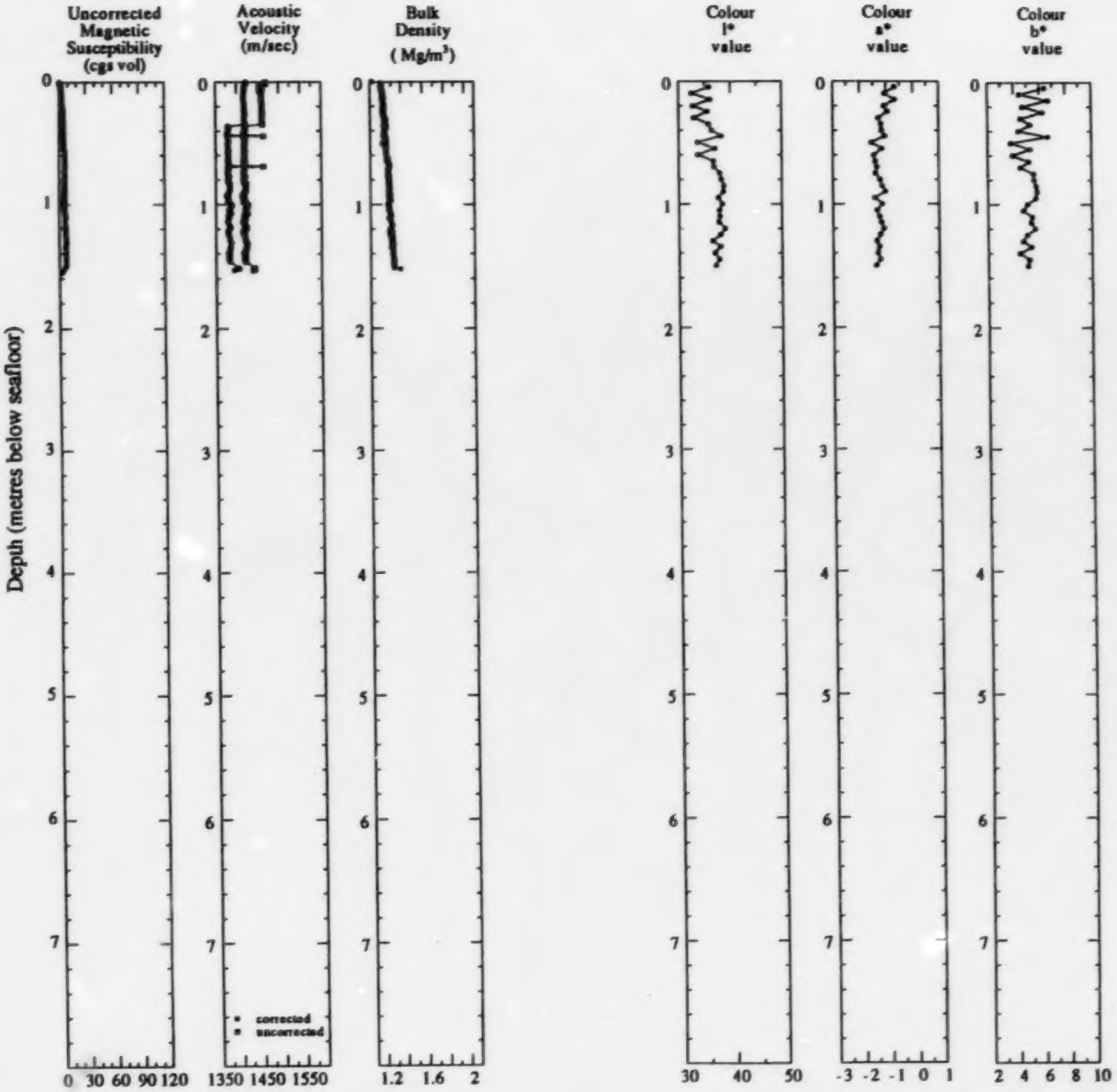
96900 Lake Winnipeg 219 gravity core



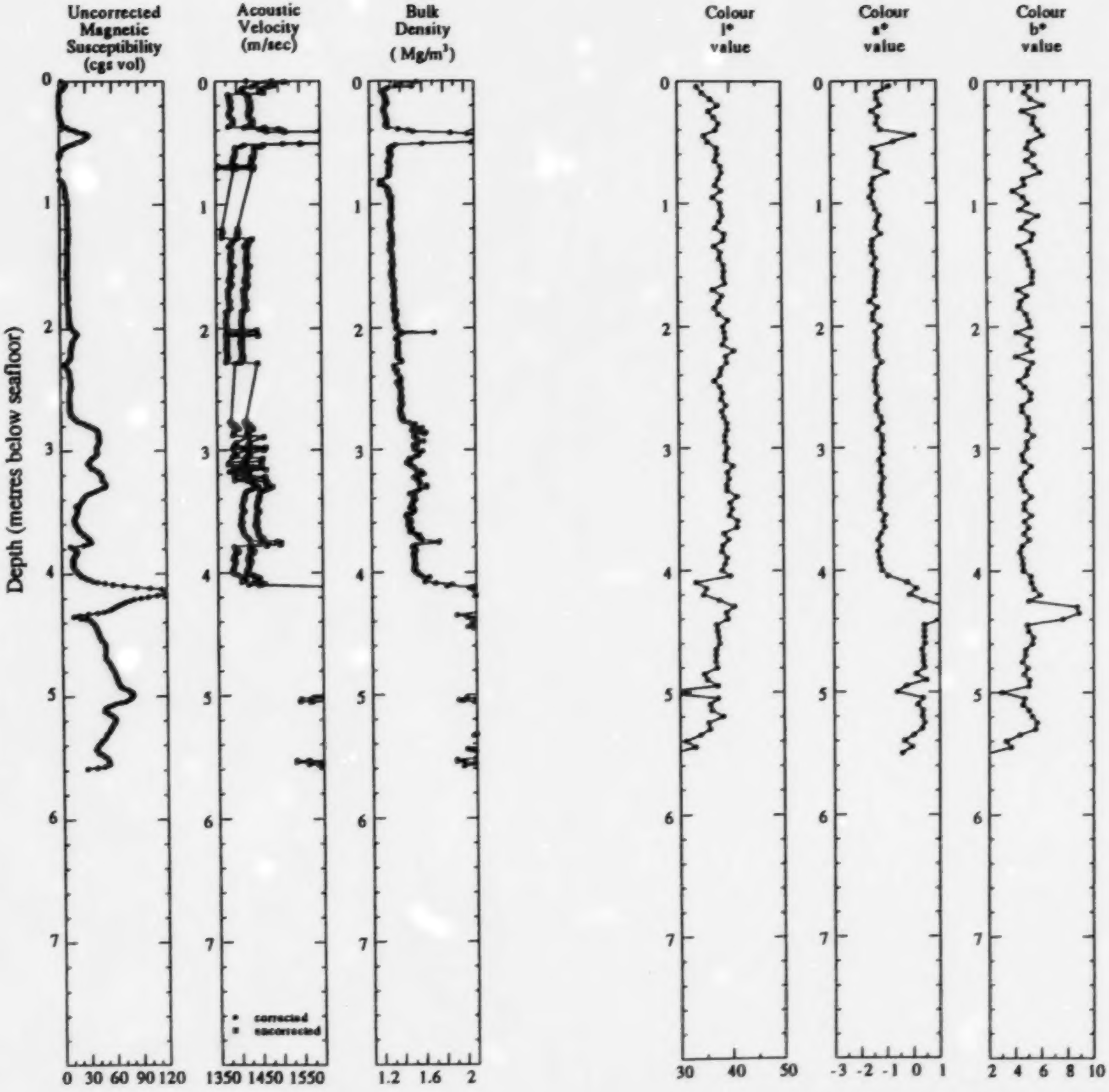
96900 Lake Winnipeg 219 piston core



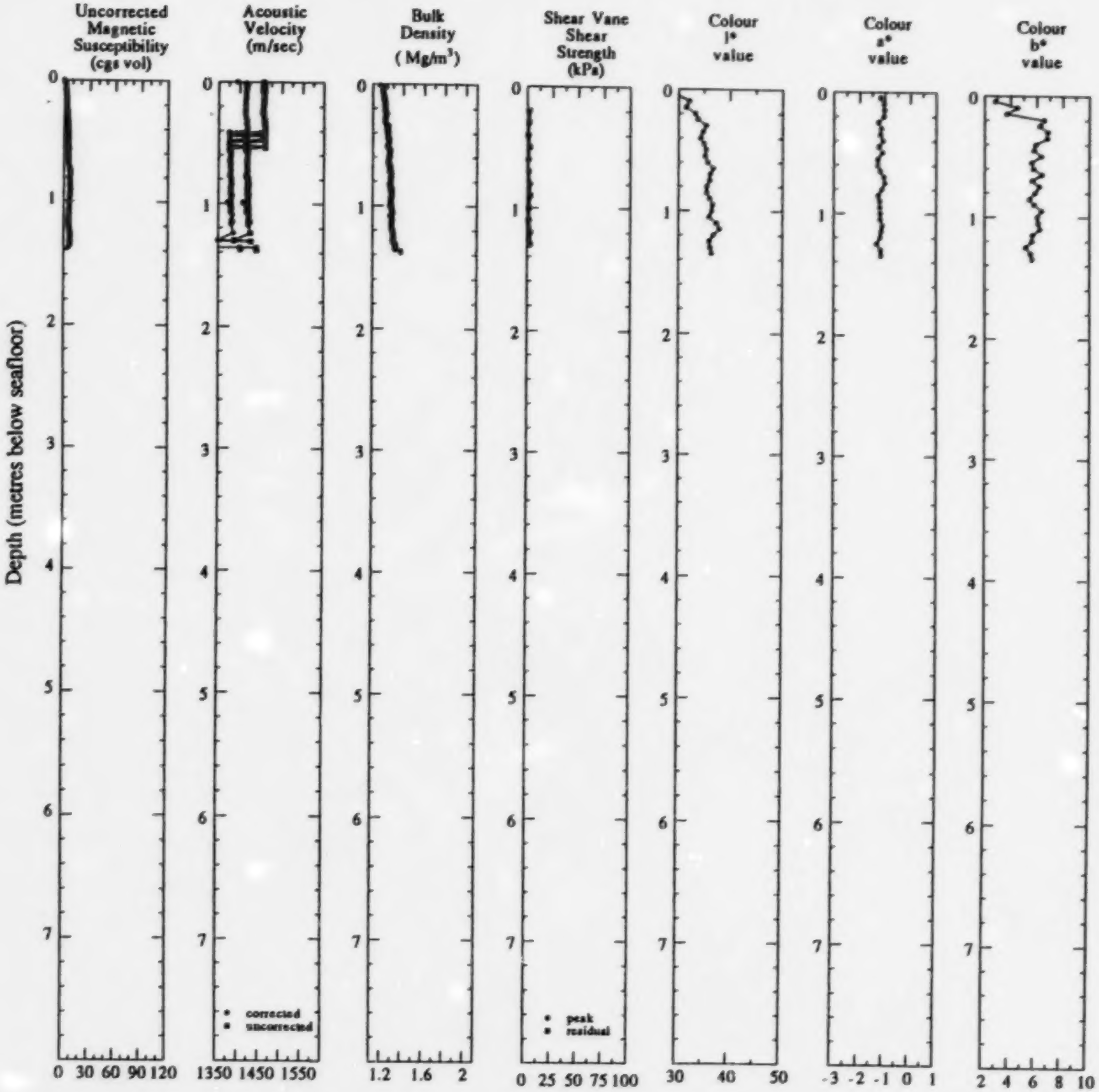
96900 Lake Winnipeg 220 gravity core



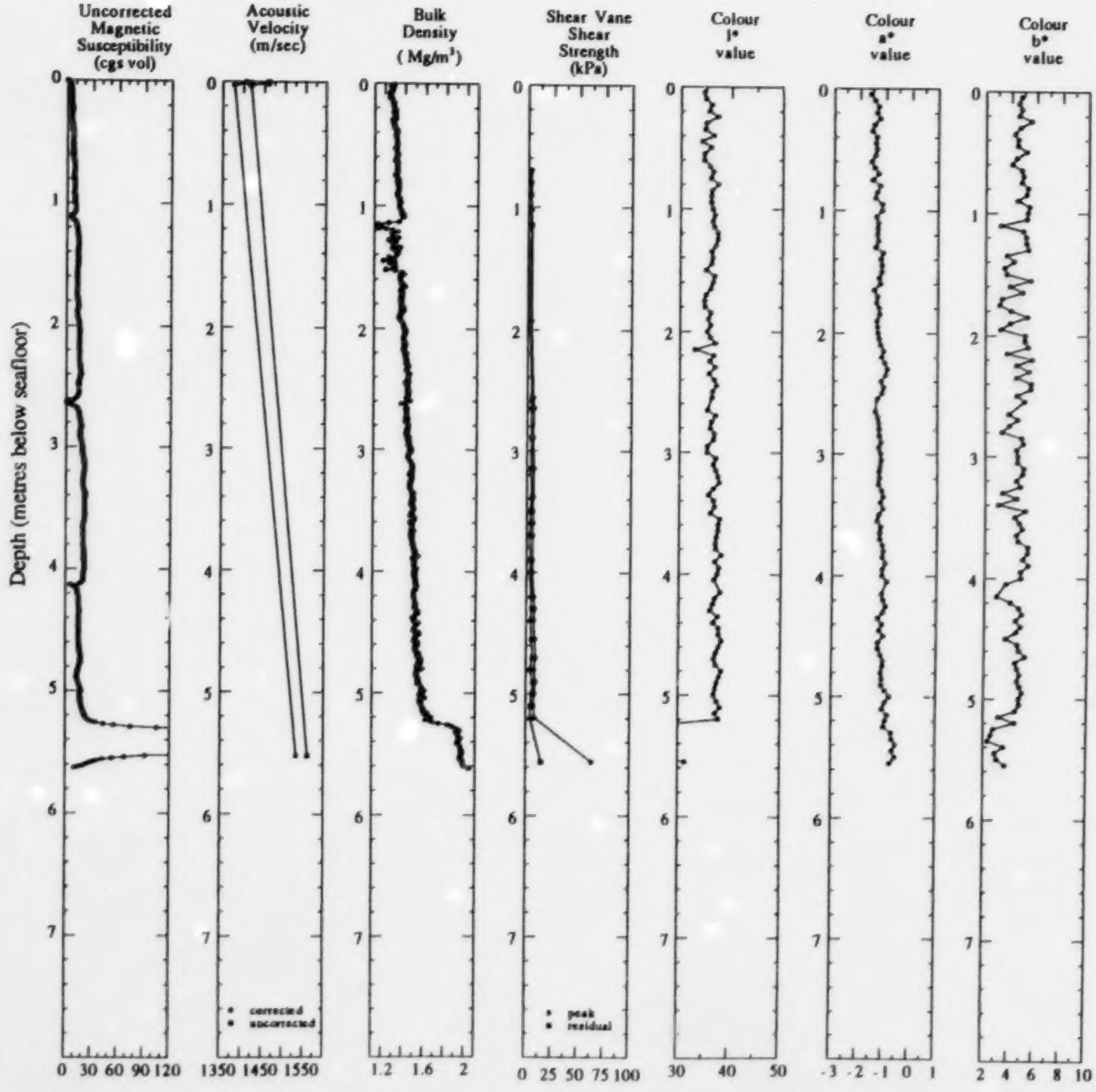
96900 Lake Winnipeg 220 piston core



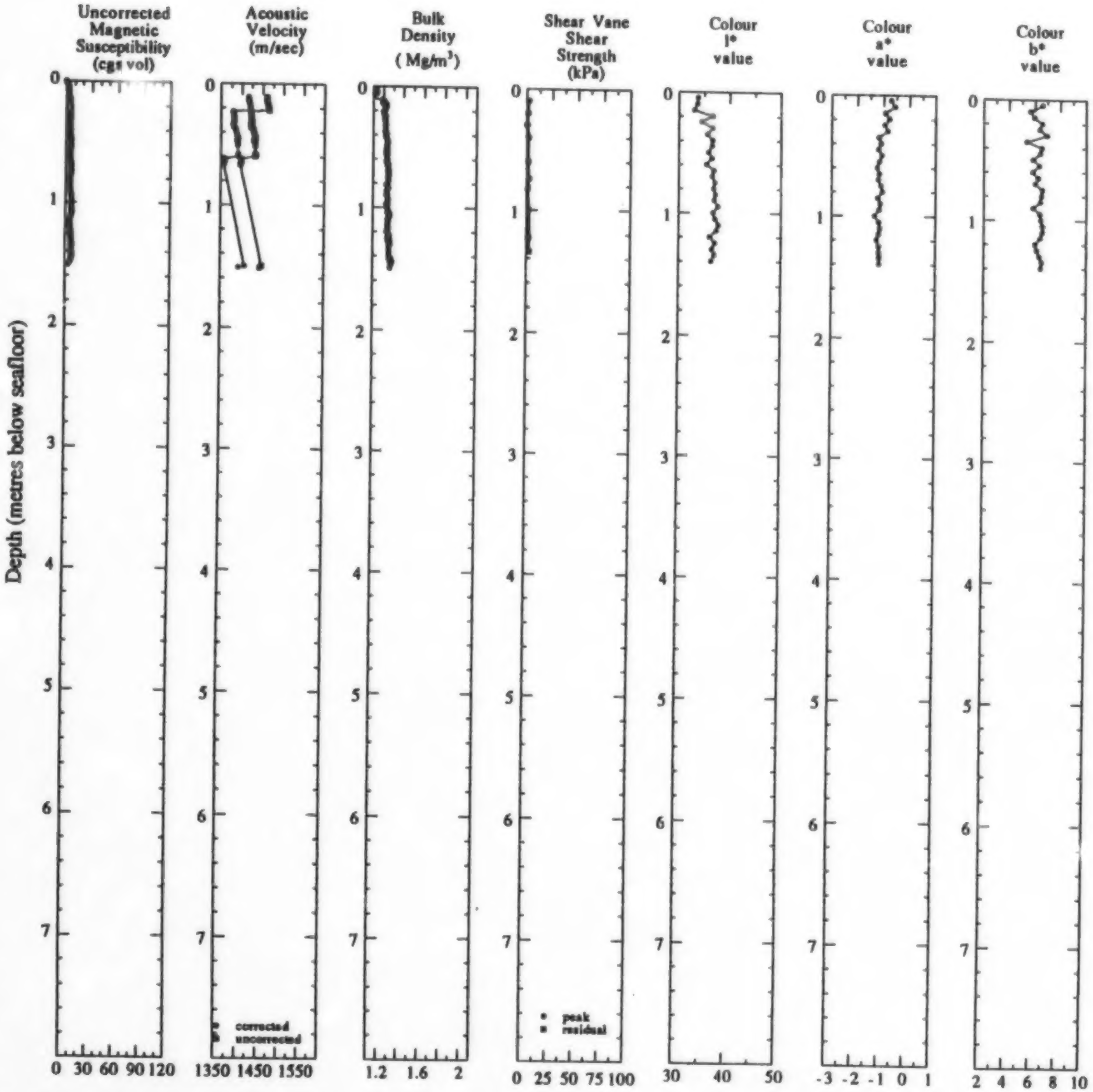
96900 Lake Winnipeg 221 gravity core



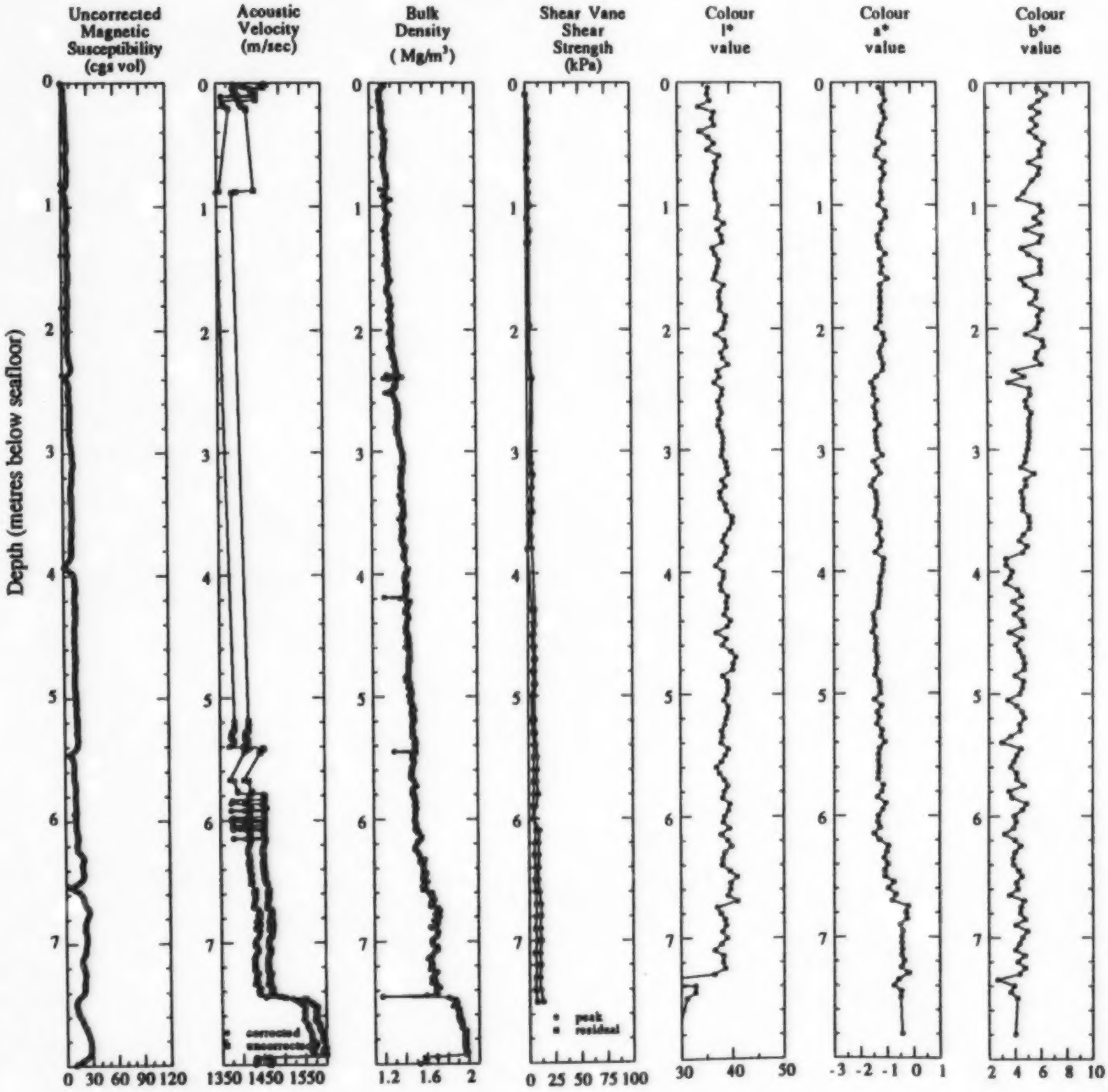
96900 Lake Winnipeg 221 piston core



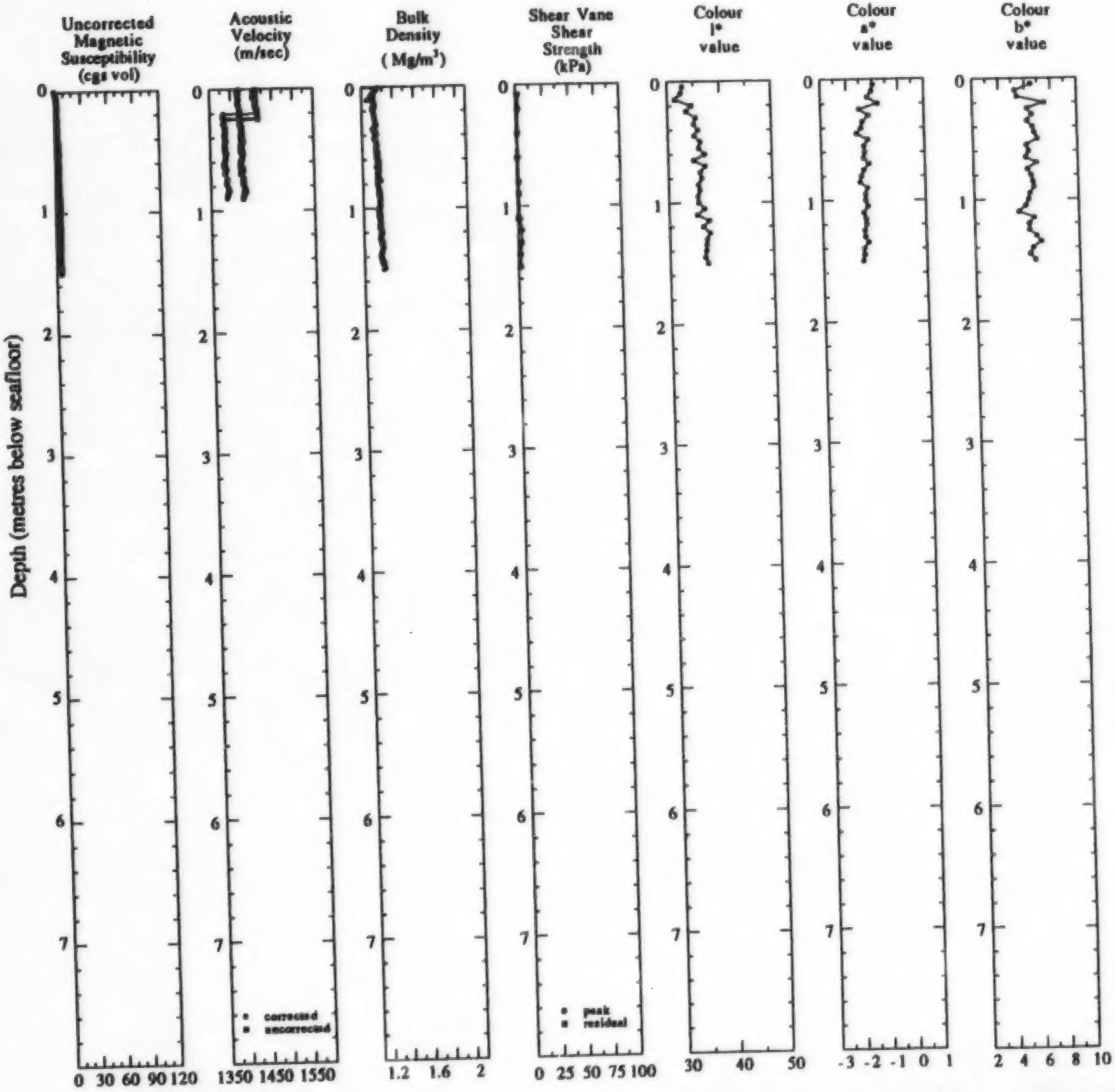
96900 Lake Winnipeg 222 gravity core



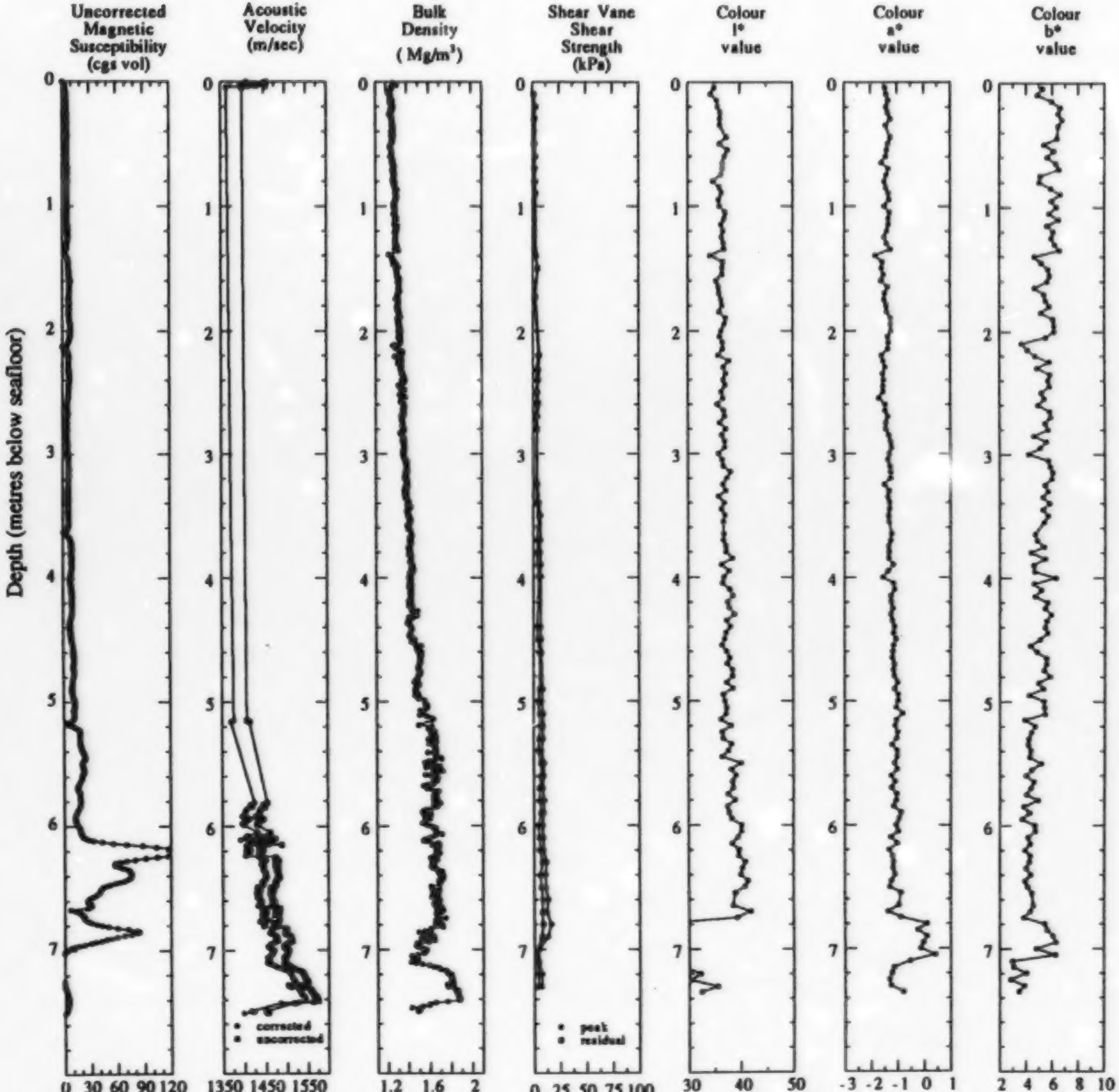
96900 Lake Winnipeg 222 piston core



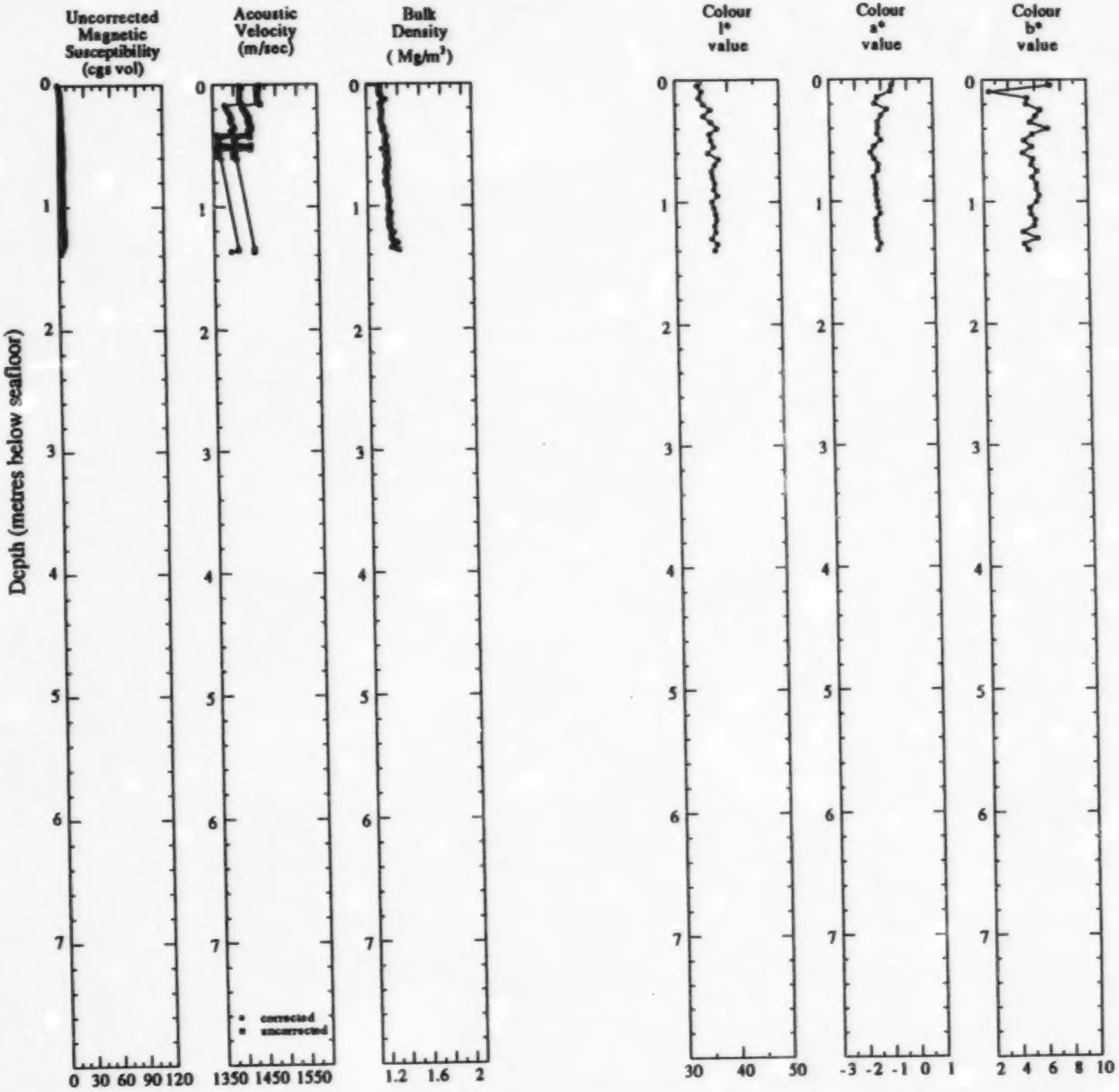
96900 Lake Winnipeg 223 gravity core



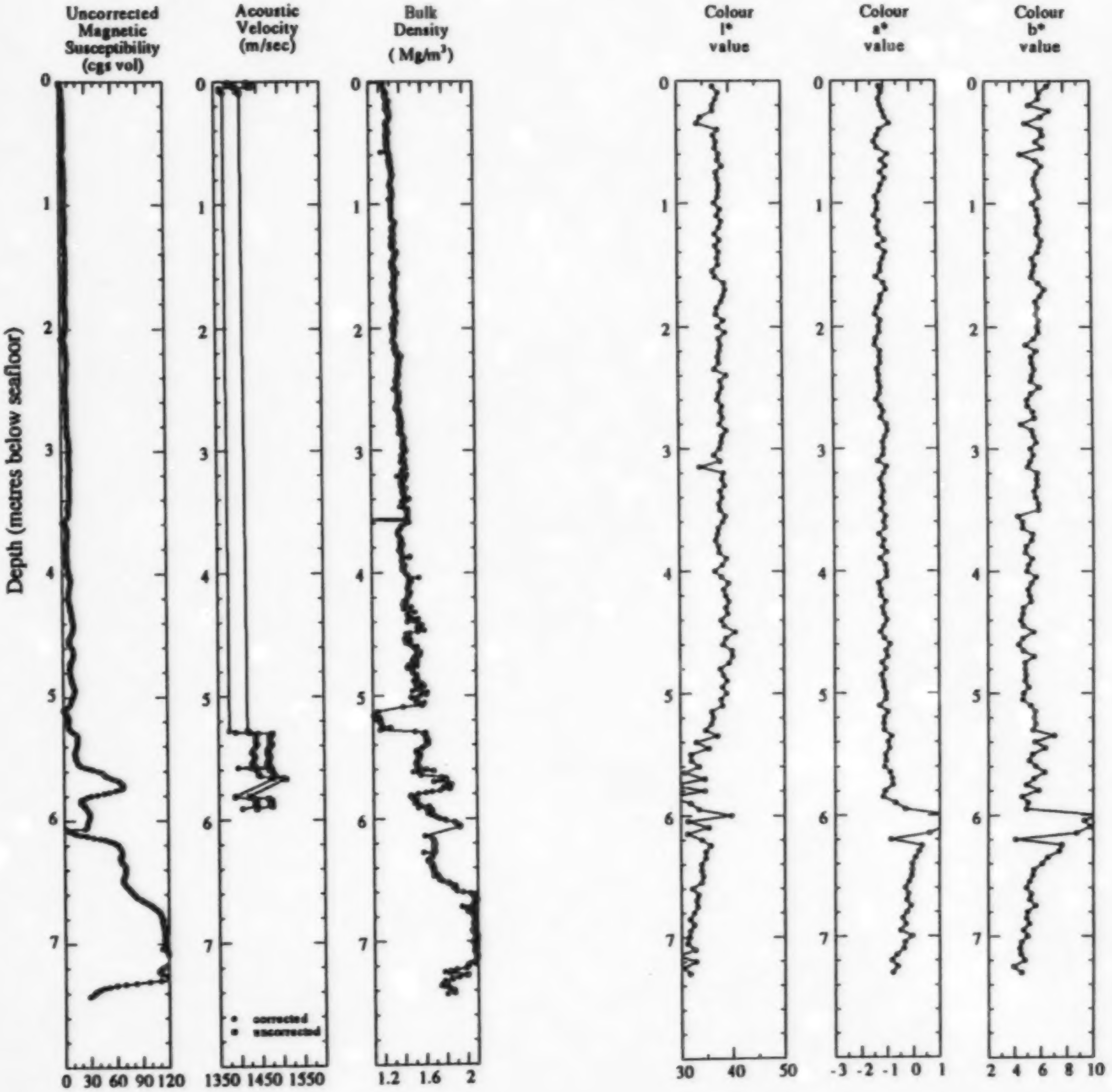
96900 Lake Winnipeg 223 piston core



96900 Lake Winnipeg 224 gravity core



96900 Lake Winnipeg 224 piston core



PART 3

96900 Lake Winnipeg

Constant Volume Subsample Data

Core Number	*Depth (m)*	*Water Content (%)**	*Bulk Density (Mg/m3)*
201 gc	0.30	219.42	1.24
	0.55	169.66	1.29
201 pc	0.43	228.85	1.20
	0.65	186.28	1.26
	3.00	108.17	1.41
	3.95	68.47	1.56
	4.70	28.65	1.93
202 gc	0.47	90.98	1.49
202 pc	0.33	128.74	1.37
	1.70	56.60	1.72
	3.75	88.34	1.57
	4.45	78.18	1.54
	5.75	61.66	1.65
203 gc	0.27	297.29	1.20
203 pc	0.89	262.23	1.20
	1.62	225.20	1.23
	4.42	132.69	1.36
	5.67	115.54	1.40
204 gc	0.85	200.99	1.25
204 pc	0.55	211.69	1.23
	1.63	165.41	1.29
	3.15	96.25	1.44
	4.45	62.42	1.55
	5.65	82.76	1.52
205 gc	0.54	229.40	1.22
	1.15	154.56	1.31
205 pc	0.24	146.48	1.32
	1.21	48.90	1.72
	2.80	81.47	1.54
	4.05	78.57	1.56
	5.31	60.58	1.64
206 gc	0.96	201.97	1.25
206 pc	0.25	196.15	1.26
	2.06	81.80	1.53
	3.65	56.56	1.66
	4.56	46.62	1.75
207 gc	0.41	215.84	1.24

Core Number	*Depth (m)*	*Water Content (%)**	*Bulk Density (Mg/m3)*
207 gc	1.16	165.42	1.31
207 pc	0.20	200.00	1.24
	0.90	144.38	1.33
	2.02	61.25	1.65
	3.32	69.39	1.59
208 gc	1.25	171.49	1.28
208 pc	0.50	197.58	1.26
	1.70	45.50	1.77
209 gc	0.42	206.87	1.23
	1.23	208.35	1.24
209 pc	0.80	136.45	1.35
212 gc	0.40	166.31	1.28
	1.15	120.76	1.37
213 gc	0.60	176.72	1.28
	1.20	146.68	1.33
213 pc	0.08	172.10	1.30
	1.40	37.59	1.84
214 gc	0.45	205.54	1.24
	1.25	166.95	1.26
214 pc	0.50	199.01	1.24
	1.60	142.16	1.33
	2.70	139.59	1.33
	3.25	-123.87	-0.16
215 gc	0.60	129.19	1.36
	1.20	101.74	1.42
215 pc	0.30	120.85	1.37
	1.30	121.69	1.37
	2.18	95.05	1.45
	3.30	78.77	1.51
216 gc	0.50	132.05	1.35
216 pc	0.20	130.50	1.36
	1.00	116.43	1.39
	2.30	51.01	1.68
	4.60	132.16	1.34
217 gc	0.80	69.13	1.57
217 pc	0.20	169.06	1.34
	1.10	66.89	1.56
	2.10	42.12	1.70
218 pc	0.30	195.13	1.24
	0.70	163.93	1.25
219 gc	0.40	258.82	1.18
219 pc	0.25	250.76	1.19
	0.70	203.27	1.23

Core Number	*Depth (m)*	*Water Content (%)**	*Bulk Density (Mg/m3)*
219 pc	4.15	92.06	1.48
220 gc	0.45	256.06	1.20
	1.20	205.30	1.24
220 pc	0.60	224.18	1.21
	1.80	186.38	1.25
	3.10	101.60	1.41
	3.90	101.45	1.42
221 gc	0.55	251.06	1.18
221 pc	0.85	161.31	1.26
	1.66	143.62	1.31
	3.55	108.72	1.39
	4.85	84.32	1.49
222 gc	0.35		1.17
222 pc	0.25	273.14	1.18
	1.05	196.77	1.22
	3.25	135.78	1.35
	4.95	113.05	1.38
	5.95	108.05	1.43
	6.85	60.80	1.64
223 gc	0.35	252.78	1.17
	1.35	209.69	1.21
223 pc	0.75	192.44	1.22
	1.45	169.98	1.25
	3.45	120.57	1.35
	3.85	117.41	1.39
	5.35	72.90	1.53
	6.65	65.54	1.60
224 gc	0.60	187.62	1.23
224 pc	0.18	201.26	1.22
	1.00	164.88	1.26
	3.00	116.91	1.36

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Shear Strength Data

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
201 pc	4.12		39.2			
	4.66		90.7			
	4.76		93.2			
	4.95		76.0			
202 pc	0.10	0.0				
	0.20	0.0				
	0.30	0.6				
	0.40	0.8				
	0.50	1.5				
	0.60	1.4				
	0.70	1.5				
	0.80	1.9				
	0.90	2.3				
	1.00	2.4				
	1.10	2.8				
	1.30			7.4	4.7	
	1.40			10.1	6.1	
	1.50			5.7	3	
	1.60			6.3	3.9	
	1.80			6.3	4.7	
	1.90			8	4.4	
	2.00			8.8	5.4	
	2.10			6.9	3.5	
	2.20			6.9	4.3	
	2.30			7.4	0.9	
	2.40			7.7	3.6	
	2.50			8	5.5	
	2.60			6.8	3.5	
	2.70			4.6	-0.2	*bad reading*
	2.80			8.7	3.8	
	2.90			8.8	5.5	
	3.01			9.6	3.9	
	3.11			10.2	5.7	*some cracking*
	3.22			9.3	4.4	
	3.30			9.5	5.5	
	3.41			9.8	4.9	*some cracking*
	3.50			10.1	4.9	
	3.61			11.5	5.5	*cracking*
	3.71			10.4	6	*some cracking*
	3.82			10.4	5.2	

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
202 pc	3.90			10.1	5.4	*small amount of cracking*
	4.00			10.7	6.6	
	4.10			11	4.7	*cracking*
	4.21			12.8	7.1	*cracking*
	4.30			11.7	5.2	*cracking*
	4.40			14	7.6	*cracking*
	4.50			13.7	6.1	*major cracking*
	4.60			12.1	5	*cracking*
	4.70			13.1	6.8	*cracking*
	4.80			13.1	5.8	*cracking*
	5.00			15.6	9.1	*cracking*
	5.10			15.4	6.8	
	5.20			12.9	6.8	*cracking*
	5.30			12.3	4.9	*cracking*
	4.50			16.5	8.7	
	5.70			13.5	5.4	*major cracking*
	5.80			6.3	3.5	
203 gc	0.10	0.0				
	0.20	0.0				
	0.30	0.2				
	0.40	0.2				
	0.50	0.2				
	0.60	0.4				
	0.70	0.4				
	0.80	0.6				
	0.90	0.6				
	1.00	1.0				
	1.10	1.0				
	1.20	1.0				
	1.30	1.0				
	1.40	1.4				
	1.50	1.2				
	1.60	1.4				
203 pc	0.10	0.0				
	0.22	0.0				
	0.30	0.2				
	0.40	0.3				
	0.50	0.4				
	0.60	0.6				
	0.70	0.8				
	0.80	0.9				
	1.04	1.0				
	1.11	1.0				
	1.17			3.6	1.7	
	1.28			2.8	2.4	
	1.73			3.9	2.5	
	1.85			4.7	3.9	

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
203 pc	1.90	1.8				
	1.95			4.4	3	
	2.05			5.2	3.6	
	2.15			4.3	3.2	
	2.25			3.0	1.6	
	2.40			4.6	3.6	
	2.78			5.4	3.5	
	3.21			5.4	2.8	
	3.30			6.0	3.8	
	3.40			6.0	3.8	*cracking*
	3.51			6.9	5.7	*cracking*
	3.60			5.0	3	
	3.70			4.4	2.4	*cracking*
	3.80			6.6	4.4	
	3.90			5.7	3.8	*cracking*
	4.00			5.8	3.8	*cracking*
	4.50			6.8	3.6	*cracking*
	4.60			6.9	4.4	*cracking*
	5.39			7.9	4.9	*cracking*
	5.63			9.1	5.7	*cracking*
	5.74			8.2	5.5	
204 gc	0.10			3	2.5	
	0.20			1.9	0.6	
	0.30			4.3	3.8	
	0.40			2	1.3	
	0.50			2.4	1.4	
	0.60			3.3	2.2	
	0.70			2.7	1.6	
	0.80			4.9	4.4	
	0.90			2.7	1.1	
	1.00			2.7	1.7	
	1.10			3.8	2.8	
	1.20			3	1.3	
	1.30			4.3	3	
	1.40			3.8	2.7	
	1.62			3.3	2	
204 pc	0.20			3.2	2	
	0.30			4.3	3.8	
	0.40			2	0.9	
	0.50			3.6	3.6	
	0.60			3	1.6	
	0.70			2.7	1.4	
	0.80			3.2	1.7	
	0.90			4.3	3.6	
	0.99			2.8	1.4	*cracking*
	1.10			2.5	1.3	
	1.20			3	1.7	

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
204 pc	1.50			3.6	2	
	1.70			2.8	1.7	*cracking*
	1.80			3.6	2.4	
	1.90			4.4	3	*some cracking*
	2.30			3.9	2.7	*cracking*
	2.40			4.7	3	*cracking*
	2.58			5.8	3.3	*cracking*
	2.67			7.1	4.7	
	3.10			4.9	2.5	*cracking*
	3.15			6.3	3.8	*cracking*
	3.20			5.2	3.2	*cracking*
	3.30			5.7	3.6	
	3.41			5.4	3.9	
	3.75			4.9	2.5	*cracking*
	3.90			6.3	4.3	*cracking*
	3.99			6.3	3.8	
	4.12			8.8	5.4	
	4.45			6.6	3.6	*cracking*
	4.80			8.8	5.7	*cracking*
	5.00			7.9	4.1	*cracking*
	5.10			7.6	5.2	*cracking*
	5.20			7.6	3.9	*cracking*
	5.30			8.2	4.7	*cracking*
	5.40			8.8	4.7	*cracking*
	5.50			7.6	4.9	
	5.70			8.8	4.4	
205 gc	0.10			3	1.7	
	0.20			1.4	0.6	
	0.30			4.3	3.8	
	0.40			2.8	1.3	
	0.50			2.8	2.8	
	0.60			3.6	2.5	
	0.70			3.2	2.4	
	0.80			3.9	1.7	
	0.90			4.1	3	
	1.00			3.3	1.6	
	1.10			2.7	2.2	
	1.20			3.8	2	
	1.30			2.5	1.7	
	1.40			5.4	4.4	
	1.50			3.5	1.9	
205 pc	0.10			4.6	4.6	
	0.20			3	1.6	
	0.30			4.3	3.6	
	0.40			3.6	2.2	
	0.50			3.6	3.2	
	0.75			3.3	2.2	

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
205 pc	0.85			3.5	1.7	
	0.95			6.6	3.8	
	1.05			6.1	2	
	1.15			6.6	4.3	
	1.25			6.6	3.3	
	1.35			8.8	6.3	
	1.45			8.5	5	
	1.55			8.3	4.4	
	1.65			8	4.1	
	1.75			8.5	4.4	
	1.85			9	4.7	
	1.95			8.3	4.1	
	2.05			4.6	5	
	2.25			10.2	6.5	
	2.35			11	5.4	
	2.45			10.9	6.1	
	2.55			11	6.8	
	2.65			12.4	6.6	
	2.75			12.4	7.4	
	2.85			13.2	7.1	
	2.95			11	6.6	
	3.05			11.5	6.8	
	3.15			10.7	4.7	
	3.25			13.5	7.7	
	3.35			12.3	5.5	
	3.45			12.9	6.1	
	3.55			11.8	6.6	
	3.75			15.3	6.3	
	3.85			12.9	5.5	
	3.95			15	6	
	4.05			17.3	9.1	
	4.15			13.7	5.5	
	4.25			14.2	6.8	
	4.35			13.9	7.4	
	4.45			14.3	7.2	
	4.55			18.9	9.6	
	4.65			17.8	8.2	
	4.75			12.4	7.2	
	4.85			15.4	8	
	4.95			12	5.8	
	5.05			11.2	5.5	
	5.15			17.6	7.2	
	5.25			15.4	6.8	
	5.35			11.3	6.9	
206 gc	0.30			3.3	2.5	
	0.40			2.2	0.6	
	0.50			3.6	2.8	

Core Number	Depth (m)	Torvane (kPa)	Pocket Penetrometer (kPa)	Shear Vane Peak (kPa)	Shear Vane Residual (kPa)	Comments
206 gc	0.60			3.8	2.8	
	0.70			3.6	2	
	0.80			3.2	1.9	
	0.90			3.2	1.4	
	1.00			4.9	4.9	
	1.10			2.7	0.9	
	1.20			3.3	2.2	
	1.30			2.7	1.7	
	1.40			3	1.6	
	1.50			4.3	3	
	1.60			3.6	1.7	
206 pc	0.10			2.8	2.2	
	0.20			3.5	2	
	0.30			3.3	2.8	
	0.40			3.9	2.7	
	0.50			2.7	1.7	
	0.60			2.8	1.7	
	0.70			7.4	4.7	
	0.80			7.9	3.8	
	0.90			8	5.2	
	1.00			10.9	5.4	
	1.10			9.5	4.7	
	1.30			12.1	6.3	
	1.40			12.9	6	
	1.60			13.9	7.7	
	1.70			14.8	7.1	
	1.80			12	6.5	
	1.90			13.1	6.8	
	2.00			13.9	7.1	
	2.10			14.2	6.9	
	2.20			13.2	7.2	
	2.30			20	8.5	
	2.40			18.7	9.5	
	2.50			13.9	6.9	
	2.60			19.1	8.7	
	2.70			16.2	8.5	
	2.80			15.6	6.8	
	2.90			14.6	6.8	
	3.00			15.8	8.2	
	3.10			16.9	7.7	
	3.20			16.1	8.3	
	3.30			15.6	7.6	
	3.40			15	8.7	
	3.50			16.1	7.1	
	3.60			16.2	7.2	
	3.70			17.8	8.7	
	3.80			14.3	6.9	

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
206 pc	3.90			18.3	8.2	
	4.00			16.1	6.5	
	4.10			17	7.9	
	4.20			13.2	6.3	
	4.30			13.5	6.9	
	4.60			22.4	9.3	
213 pc	1.37		75.0			
214 pc	3.94		49.0			
215 pc	4.10		31.9			
	4.37		23.0			
	4.60		37.3			
221 gc	0.20			2.5	1.7	
	0.30			2.7	2	
	0.40			1.9	0.8	
	0.50			3.5	2.8	
	0.60			2	1.3	
	0.70			2.2	1.9	
	0.80			3.3	2.5	
	0.90			3.8	3	
	1.00			2.7	1.6	
	1.10			2.8	1.4	
	1.20			3.6	2.7	
	1.30			3.6	2.8	
221 pc	0.70			3.3	2.2	
	0.80			3.3	2.2	
	0.90			3.2	2.5	
	1.02			3.2	2.5	
	1.15			4.4	3.3	
	1.93			4.4	2.7	
	2.56			6.5	4.9	
	2.65			7.1	4.1	
	2.89			6	4.1	
	3.15			6.9	4.3	
	3.38			6.8	5.2	
	3.50			6.3	3.6	
	3.60			6.6	4.1	
	3.70			6	3.3	
	3.90			6.3	4.4	
	4.00			6.3	3.6	
	4.20			7.7	5.2	
	4.30			8.7	5.7	
	4.39			8	5	
	4.55			8.7	5.5	
	4.70			9.8	6.8	
	4.80			8.2	4.4	
	4.90			9.8	7.1	
	5.00			8.7	6	

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
221 pc	5.10			7.9	5	
	5.20			9	4.9	
	5.56			63.8	15	
	5.72			121.3	137.7	
222 gc	0.10			2.4	1.7	
	0.20			1.9	1.1	
	0.30			1.4	0.3	
	0.40			2.4	1.6	
	0.60			2.2	1.7	
	0.74			2.7	2.4	
	0.83			2	1.1	
	1.00			3.3	2.2	
	1.23			3	2	
	1.34			3.5	3.5	
222 pc	0.10			1.4	0.5	
	0.20			2.4	1.7	
	0.31			3	2.7	
	0.49			3.3	2.4	
	0.62			2.8	1.9	
	0.70			1.7	1.3	
	0.80			3.2	2.5	
	0.90			3.2	2.2	
	1.00			4.3	3.8	
	1.10			2.2	1.1	
	1.20			3.9	3.3	
	1.30			3.2	1.4	
	1.97			3.6	3.3	
	2.20			3.2	1.9	
	2.40			5.4	4.1	
	3.10			4.9	2.4	
	3.20			6	4.1	
	3.30			5.2	3.9	
	3.40			4.9	3.3	
	3.50			5.8	4.4	
	3.60			3.8	1.9	
	3.70			4.3	3.3	
	3.80			4.6	0	
	4.30			7.2	4.4	
	4.42			7.4	5.5	
	4.50			6.1	3.9	
	4.60			6.6	4.7	
	4.70			7.9	5.4	
	4.80			6.6	4.6	
	4.90			7.7	5.5	
	5.00			6	3.8	
	5.20			6.6	3.6	
	5.30			7.2	5	

Core Number	*Depth (m)*	*Torvane (kPa)*	*Pocket Penetrometer - (kPa)*	*Shear Vane Peak (kPa)*	*Shear Vane Residual (kPa)*	*Comments*
222 pc	5.40			8	5.4	
	5.50			8.8	5.2	
	5.60			8.5	5.7	
	5.70			8.3	4.7	
	5.80			9.6	5.5	
	5.90			7.4	4.4	
	6.00			4.6	5	*core disturbed*
	6.10			10.6	6.9	
	6.20			9.6	6.1	
	6.30			9.6	5.2	
	6.40			9.6	7.1	
	6.50			9.3	5.8	
	6.60			10.1	6.6	
	6.70			11.8	7.1	
	6.80			11.7	7.2	
	6.90			11.2	6.5	
	7.00			12	8.2	
	7.10			10.7	5.8	
	7.20			11.7	7.9	
	7.30			10.6	6.6	
	7.40			11.2	6	
	7.50			13.4	8	
223 gc	0.08			2.7	1.7	
	0.20			2.4	1.6	
	0.40			2.2	1.4	
	0.60			1.9	0.8	
	0.80			2.2	1.6	
	0.90			2.2	1.9	
	1.10			2.4	0.8	
	1.20			3.9	3.2	
	1.30			3.8	3	
	1.40			2.8	1.6	
	1.50			2.7	1.6	
223 pc	0.10			1.7	1.1	
	0.20			3.3	3	
	0.30			2.7	1.7	
	0.50			2.4	1.4	
	0.60			3.2	2.2	
	0.70			2.5	1.6	
	0.80			3	1.7	
	0.90			3.5	2.5	
	1.40			3.8	2.4	
	1.50			5.2	5	
	1.73			3	1.6	
	2.20			6.6	5.5	
	2.32			5.5	3.5	
	2.40			5.5	4.1	

Core Number	Depth (m)	Torvane (kPa)	Pocket Penetrometer (kPa)	Shear Vane Peak (kPa)	Shear Vane Residual (kPa)	Comments
223 pc	2.50			4.6	3	
	2.59			5.4	3.8	
	2.70			4.6	2.5	
	2.80			4.4	3.6	
	3.25			4.9	3	
	3.40			5.5	3.5	
	3.50			6.9	5.4	
	3.70			7.1	4.4	
	3.80			6.8	4.1	
	3.90			7.6	4.7	
	3.99			7.4	5.5	
	4.40			7.1	4.1	
	4.50			7.9	5	
	4.61			8	6.1	
	4.90			9.1	6.5	
	5.00			7.7	4.7	
	5.10			9.8	6.5	
	5.20			9.3	6.8	
	5.30			9	5.5	
	5.40			7.7	4.6	
	5.50			10.1	7.4	
	5.60			9.8	7.1	
	5.70			8.7	5.7	
	5.80			9.9	6	
	5.90			9.8	7.1	
	6.00			8.5	4.9	
	6.10			9.1	5.8	
	6.20			9.1	5.4	
	6.30			12.3	8.2	
	6.40			11.2	6.1	
	6.50			11.2	6.9	
	6.60			13.9	8.7	
	6.70			12.1	8.3	
	6.80			16.5	8.7	
	6.90			13.2	7.6	
	7.00			5	3.5	
	7.10			4.7	2.7	
	7.20			7.6	4.4	
	7.30			7.1	4.1	

Appendix 10.4

Summary core logs and corresponding seismostratigraphic sequences

C.F.M. Lewis[1], B.J. Todd[1], D.L. Forbes[1], E. Nielsen[2] and L.H. Thorleifson[3]

1. Geological Survey of Canada (Atlantic)
2. Manitoba Energy and Mines
3. Geological Survey of Canada, Ottawa

Summary logs of cores collected in August and early September of 1996 at 22 sites in Lake Winnipeg are presented in this appendix along with seismic profiles (2-6 kHz) annotated for core location and seismostratigraphic sequences. The locations of the core sites are indicated in Figure 1.

At most sites, two 10-cm diameter cores were attempted using a 2-m gravity corer and a piston corer of 9 m length. A split piston was used at sites 201 to 209, and a solid piston at sites 213 to 224. No cores were collected at sites 210 and 211. Only a gravity core could be acquired at site 212 owing to rough weather.

Lithologic descriptions of the cored sediments are based, in part on X-ray videos of the whole core, but mostly on visual observations and photographs of the longitudinal core face immediately after the plastic core liner and core had been split in the laboratory in late October 1996. Sediment texture was subjectively assessed and cross-checked with grain-size analyses where available (Forbes; this volume, Appendix 10.7). Colour was judged by comparison with sample colours in the Munsell Soil Color system (Munsell Color Division, 1971). Calcium carbonate content of the sediment (calcareousness) was estimated approximately by its effervescence upon application of a few drops of 10 % HCl acid. Sediment consistency is a subjective estimation of relative sediment strength based on its ability to hold its shape or to resist indentation by finger pressure: very soft = sediment flows under its own weight, soft = sediment holds its shape and is indented with little resistance, firm = sediment is easily indented, stiff = sediment is indented with difficulty, and hard = sediment cannot be indented by finger pressure. The summary core log pages carry a written description of both gravity and piston cores where both were recovered at a site, but only the piston core logs are illustrated diagrammatically. Conventional radiocarbon ages obtained by accelerator mass spectrometry (AMS) on fossils extracted from the sediment are listed in years before present (1950 AD) in the written descriptions, and shown in ka notation (thousands of years before present) on the diagrammatic core logs. Note that shell dates are uncorrected; dates can be corrected by subtracting 255 years (Lewis et al., this volume).

Further information is available about the acquisition of seismic profiles and sediment cores in Todd (this volume). Todd et al. (1998) define the seismostratigraphy of the Lake Agassiz and Lake Winnipeg sediments. Jarrett (this volume a, b) and Moran and Jarrett (1998) give measures and interpretation of the sediment physical properties. Lewis et al. (this volume) give information on corer performance, and stratigraphy and interpretation of the sediments. Counts and thickness measurements of Lake Agassiz rhythmites in selected cores are provided by Davison et al. (this volume). Telka (this volume a, b) explain the paleo-environmental significance of macrofossils and list details of the AMS dating. Rodrigues (this volume) provides a description of sediment zonation based on ostracodes, molluscs and other organisms. The isotopic composition of ostracodes in cores 205 and 206 is given by Rodrigues and Lewis (this volume). Risberg (this volume) provides information on the diatom stratigraphy of cores 201, 204 and 205.

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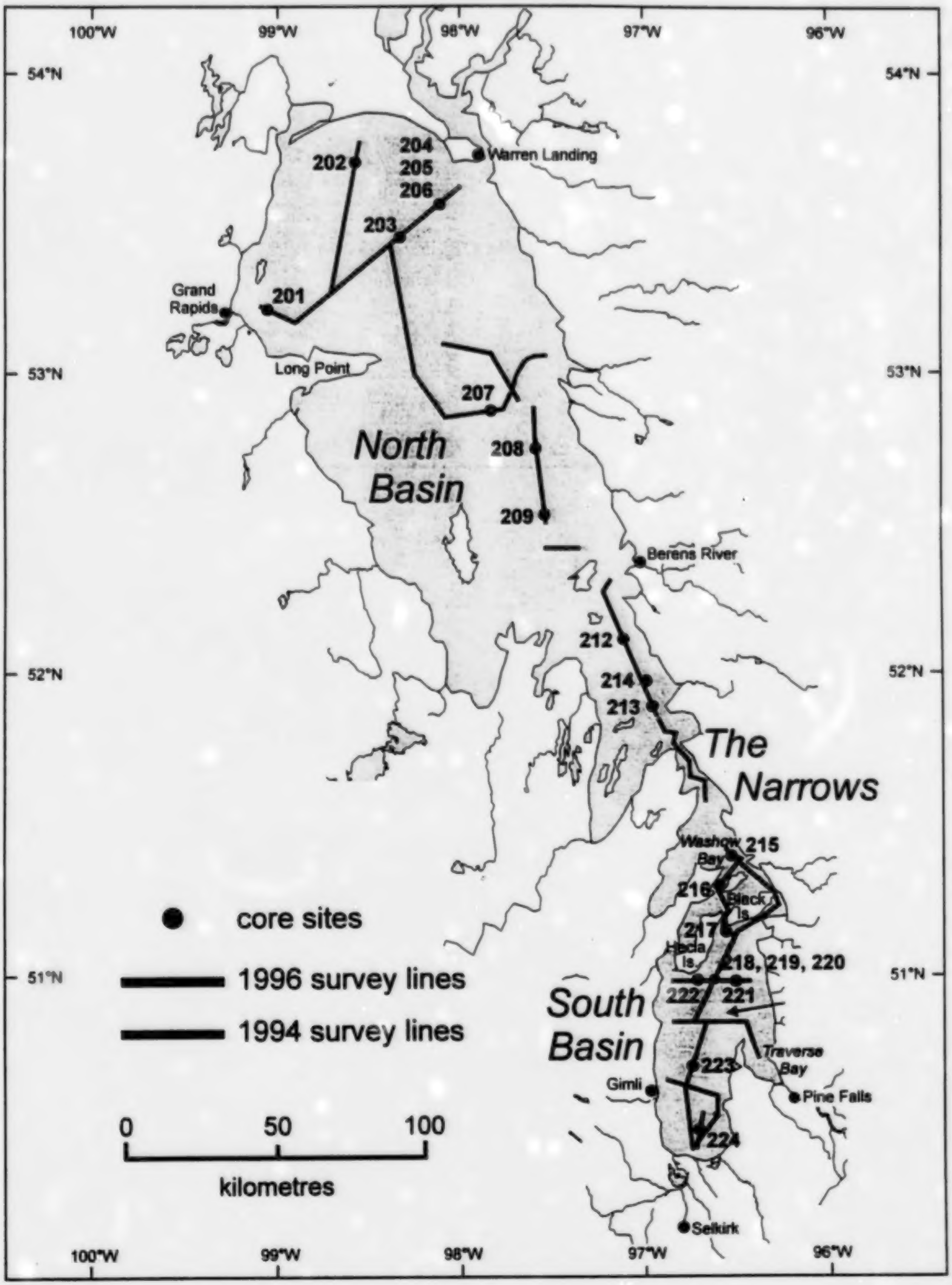
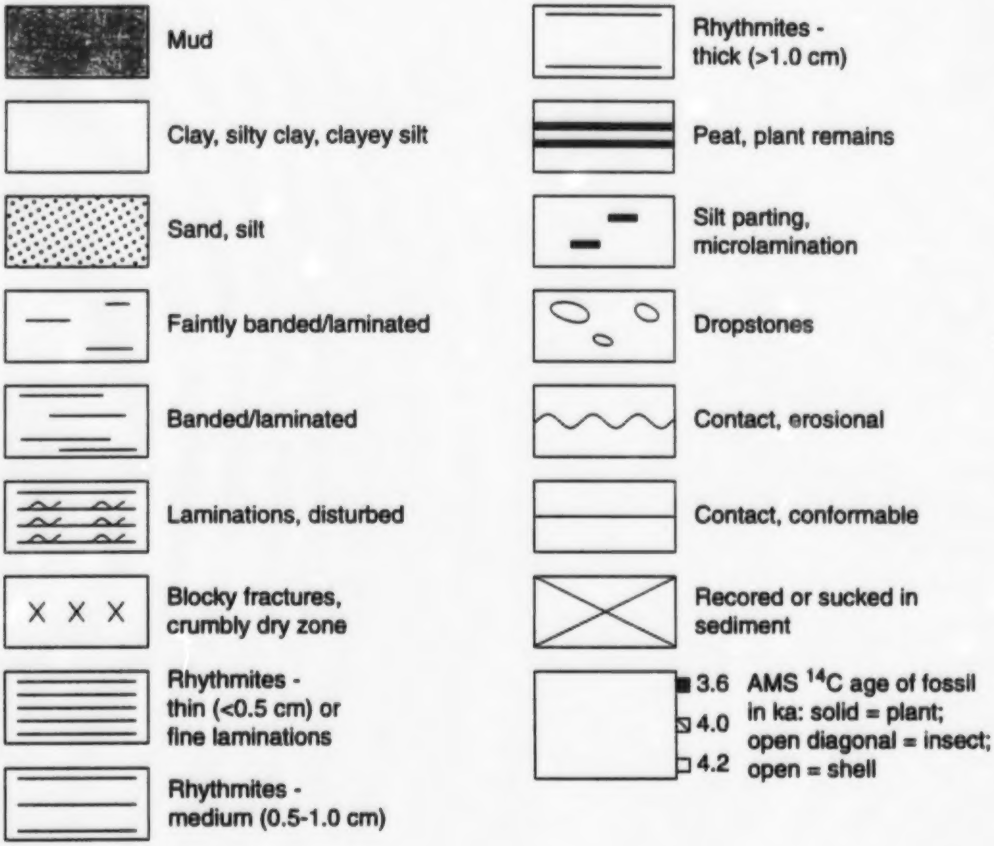
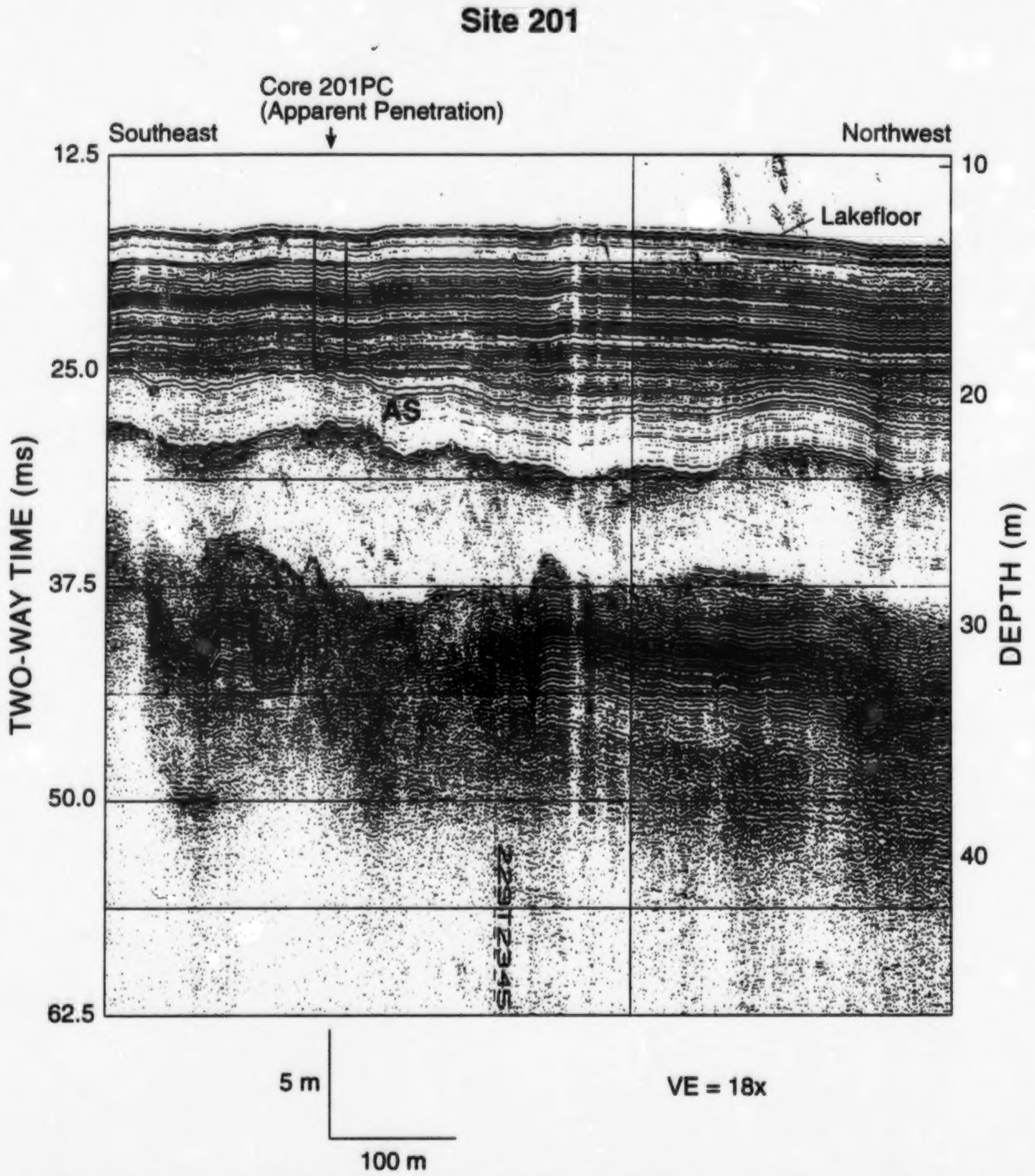

100°W
99°W
98°W
97°W
96°W
54°N
53°N
52°N
51°N
204
205
206
202
Warren Landing
203
Grand Rapids
201
Long Point
207
North Basin
208
209
Berens River
212
214
213
The Narrows
Washow Bay
215
216
Black Is.
217
Hecla Is.
218, 219, 220
222
221
South Basin
Traverse Bay
223
Gimli
Pine Falls
224
Selkirk
core sites
1996 survey lines
1994 survey lines
0
50
100
kilometres

Figure 1. Map of Lake Winnipeg showing locations of 1996 core sites and seismic profiles.

Legend for Graphic Core Logs


Mud
Clay, silty clay, clayey silt
Sand, silt
Faintly banded/laminated
Banded/laminated
Laminations, disturbed
Blocky fractures, crumbly dry zone
Rhythmites - thin (<0.5 cm) or fine laminations
Rhythmites - medium (0.5-1.0 cm)
Rhythmites - thick (>1.0 cm)
Peat, plant remains
Silt parting, microlamination
Dropstones
Contact, erosional
Contact, conformable
Recored or sucked in sediment
3.6
4.0
4.2
AMS ¹⁴C age of fossil in ka: solid = plant; open diagonal = insect; open = shell

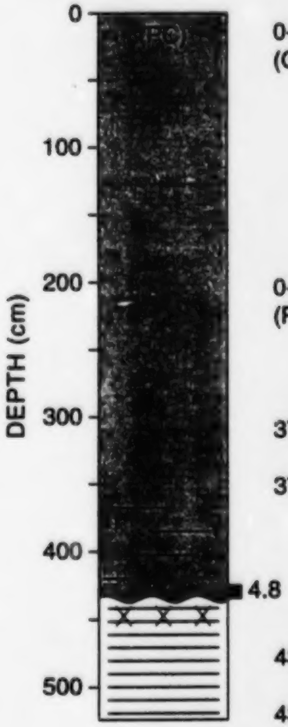


High resolution seismic reflection (Seistec) profile through core site 201 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AS = Agassiz Sequence (undifferentiated), AU = Agassiz Unconformity. (Seistec record, line NB9, Day 229, 1994, 2345 UTC).

Site 201

Latitude:	53° 12.0' N	Gravity Core (GC):	10x192 cm
Longitude:	99° 06.9' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.8 m asl, 13.0 m	Piston (Split) Core (PC):	10x525 cm
Date (Julian):	235/1937 (GC) and 235/2109 (PC)	PC Apparent Penetration:	600 cm

Lithology:



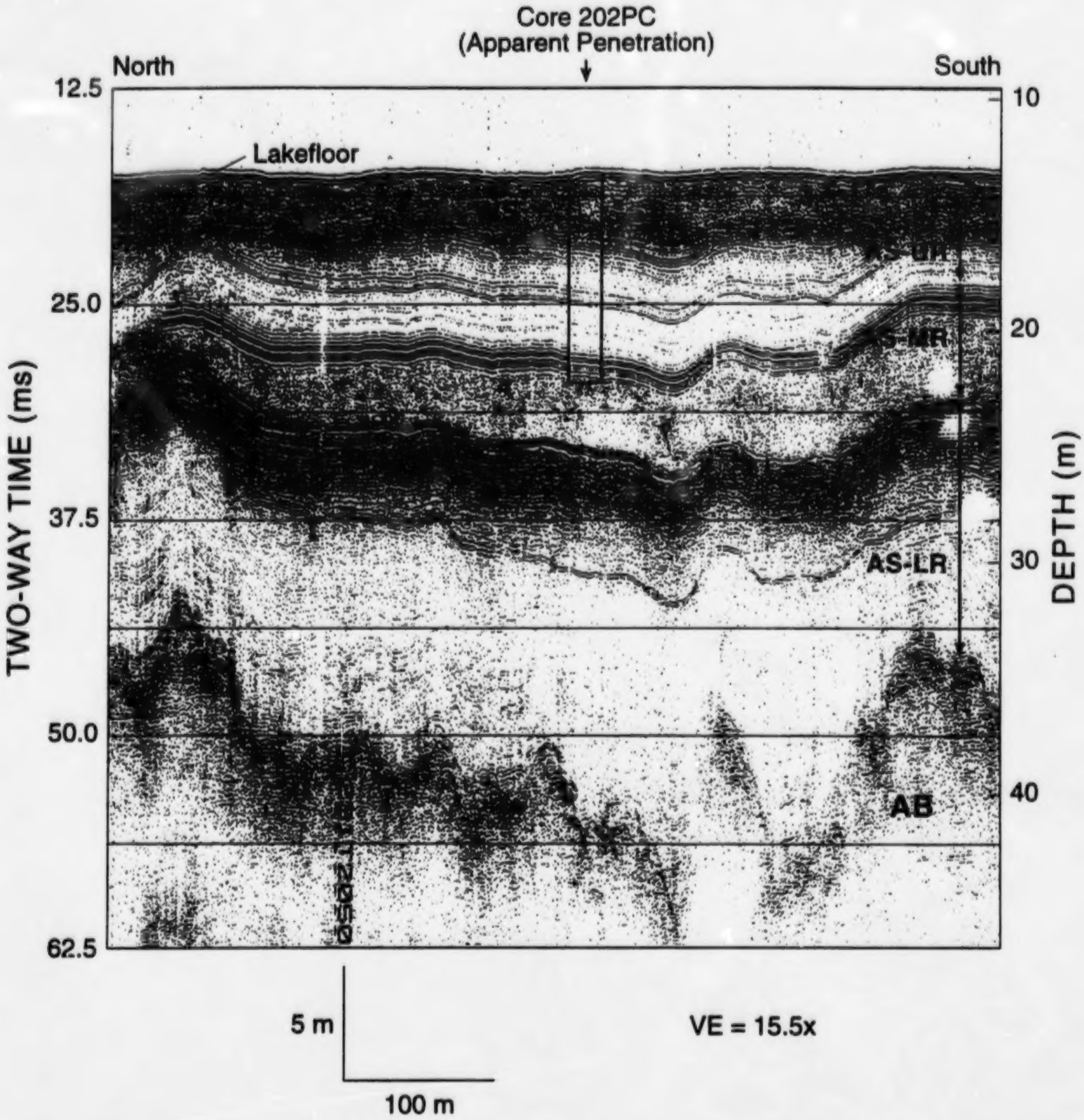
0-192 cm (GC)	**Silt-clay mud;** soft, dark gray (5Y4/1), noncalcareous. Black mottled at top grading to massive below 37 cm with rare, intermittent, faint laminations at 131-133, 149-153, 160-164 and 169-173 cm.
0-370 cm (PC)	**Silt-clay mud;** soft, dark gray (5Y4/1), black to mottled dark gray in upper 45 cm. Noncalcareous. Massive to rarely, faintly laminated at 156-160,168-170 and 226-228 cm.
370 cm	**Contact;** weak, transitional.
370-439 cm	**Silt-clay mud;** soft dark gray (5Y4.5/1). Diffusely, faintly, discontinuously, irregularly laminated and mottled. Occasional small white flecks. At 434-439 cm, charred spruce needles dated 4800±70 (CAMS 35499).
439 cm	**Contact;** sharp, erosional.
439-525 cm	**Silty clay;** stiff, finely laminated with blocky angular fractures and crumbly texture in upper 20 cm. Two faceted 1-cm pebbles at 441 cm (dropstones?). White silt partings below 470 cm.

Core intervals equivalent to seismostratigraphic sequences:

0-439 cm	Winnipeg Sequence (Lake Winnipeg sediments).
439-525 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 201GC and 201PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 202

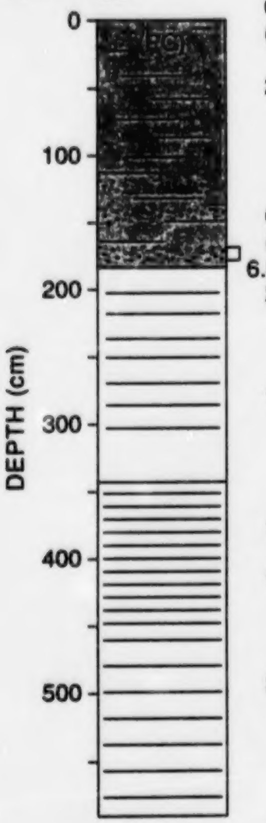


High resolution seismic reflection (Seistec) profile through core site 202 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence (AS), UR = Upper Reflective Interval, MR = Middle Reflective Interval, LR = Lower Reflective Interval. (Seistec record, line NB11, Day 231, 1994, 2050 UTC).

Site 202

Latitude:	53° 43.2' N	Gravity Core (GC):	10x135 cm
Longitude:	98° 36.2' W	GC Apparent Penetration:	150 cm
Lake Level, Depth:	217.8 m asl, 13.6 m	Piston (Split) Core (PC):	10x589 cm
Date (Julian):	236/1750 (GC) and 243/1832 (PC)	PC Apparent Penetration:	896 cm

Lithology:



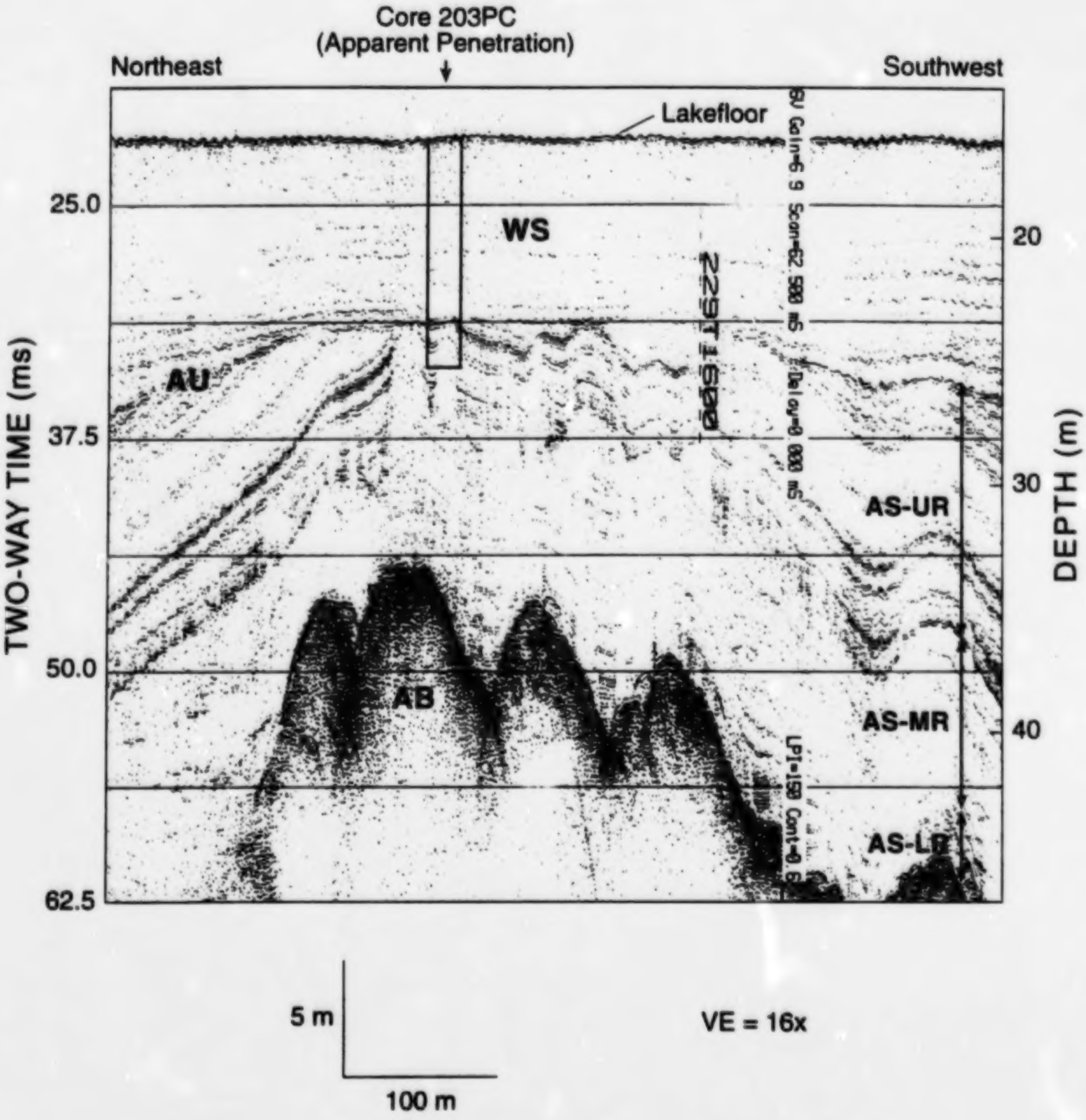
0-25 cm (GC)	**Silt-clay mud;** soft, dark olive gray (5Y3/2). Massive to diffusely banded 0-3 cm, black-mottled 3-8 cm and massive 8-25 cm.
25-135 cm	**Silt-clay mud;** soft, rhythmically banded to laminated. Dark olive gray (5Y3/2) calcareous, cm-scale layers alternating with paler but prominent olive gray (5Y5/2) mm-scale laminations which are more calcareous.
0-20 cm (PC)	**Silt-clay mud;** very soft to soft, dark olive gray (5Y3/2). Noncalcareous. Massive to diffusely banded and mottled, sparse black FeS staining.
20-116 cm	**Silt-clay mud;** soft, calcareous, rhythmically banded to laminated. Dark olive gray (5Y3/2), banded with prominent pale cream laminae (5Y5/2, olive gray) 1-3 mm thick, every 3-5 cm.
116-179 cm	**Clayey silt mud and sand;** soft, dark olive gray (5Y3/2), calcareous. Massive to faintly laminated with silt, sandy silt and sand beds, blebs and lenses. At 174-179 cm, ostracodes dated 6810±60 (CAMS 32192).
179 cm	**Contact;** conformable.
179-341 cm	**Clay;** soft, laminated, calcareous. Distinct gray (5Y2.5/1) laminae 0.5-4 mm, becoming dark olive gray (5Y3/2), indistinct and diffuse below 290 cm. Indistinct basal contact.
341-579 cm	**Clay;** soft-firm, laminated, calcareous. Probable thin rhythmites 1-3 mm, couplets consisting of creamy-looking lighter gray (5Y 4/2 and 5Y4/1) grading up to darker, olive gray (5Y4/2 and 5Y5/1) laminae. Proportion of lighter gray clay increases in couplets below 440 cm so rhythmites thicken to 1cm at 507 cm. Rhythmites 2-3 cm thick at 538-546 cm show >6 laminae in lighter layers. Microfaults throughout (probable coring disturbance due to faulty action of split piston).
579-589 cm	Soft mud (recored material).

Core intervals equivalent to seismostratigraphic sequences:

0-179? cm	Winnipeg Sequence.
179?-579? cm	Agassiz Sequence.

Summary lithologic log for cores 202GC and 202PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 203

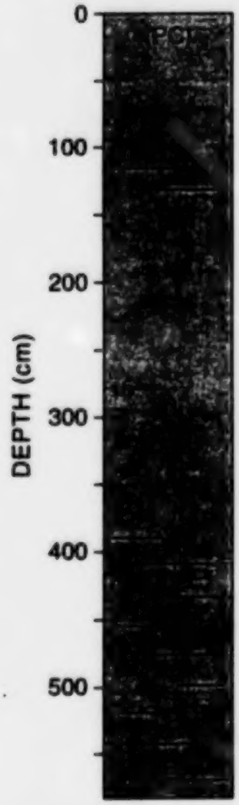


High resolution seismic reflection (Seistec) profile through core site 203 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence (AS), UR = Upper Reflective Interval, MR = Middle Reflective Interval, LR = Lower Reflective Interval. (Seistec record, line NB9, Day 229, 1994, 1600 UTC).

Site 203

Latitude:	53° 27.3' N	Gravity Core (GC):	10x164 cm
Longitude:	98° 21.5' W	GC Apparent Penetration:	175 cm
Lake Level, Depth:	217.8 m asl, 16.5 m	Piston (Split) Core (PC):	10x583 cm
Date (Julian):	237/1613 (GC) and 237/1643 (PC)	PC Apparent Penetration:	892 cm

Lithology:



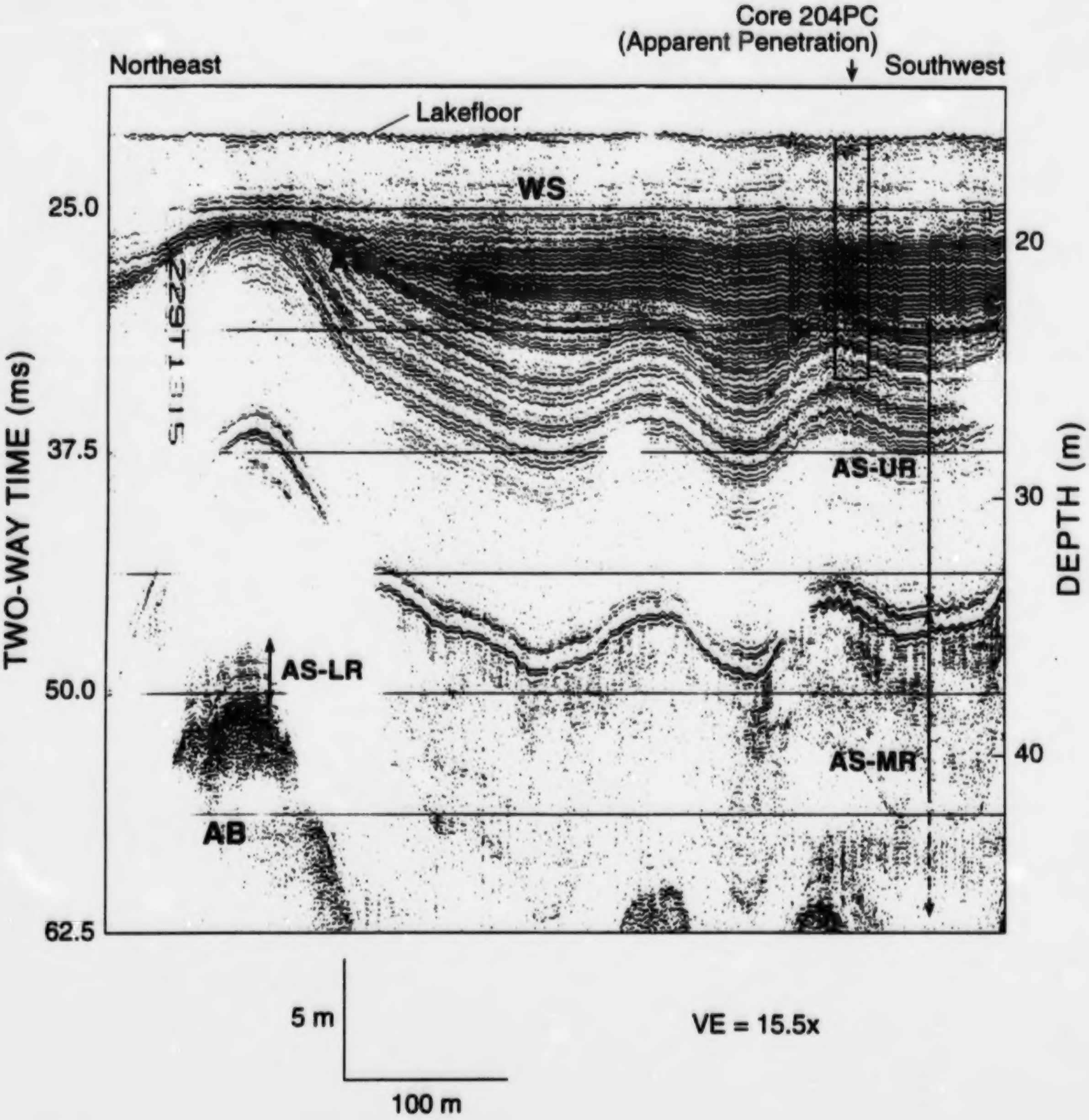
0-14 cm (GC)	**Clay mud;** very soft, very dark gray (5Y3/1), noncalcareous. Surface dark brown (10YR3/3) oxidized layer, 0-0.5 cm, then massive with black specks of FeS grading to unit below.
14-164 cm	**Clay mud;** soft, dark gray (5Y4/1), noncalcareous with trace of silt. Massive.
0-390 cm (PC)	**Clay mud;** soft, dark gray (5Y4/1), noncalcareous with trace of silt. Rare black FeS specks in upper 30 cm. Massive, with slight mottling; diffuse, incipient banding 114-132, 317-320 cm.
390-583 cm	**Clay mud;** soft, dark gray (5Y4/1), noncalcareous. Faintly banded comprising thin 2-5 mm paler diffuse and discontinuous laminations. Occasional zones of black FeS specks, 520-521, 524-528 and 570-571 cm.

Core intervals equivalent to seismostratigraphic sequences:

0-583 cm	Winnipeg Sequence (Lake Winnipeg sediments).

Summary lithologic log for cores 203GC and 203PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 204

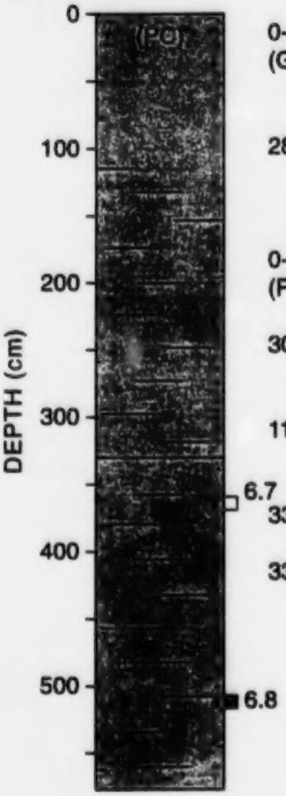


High resolution seismic reflection (Seistec) profile near core site 204 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence (AS), UR = Upper Reflective Interval, MR = Middle Reflective Interval, LR = Lower Reflective Interval. (Seistec record, line NB9, Day 229, 1994, 1315 UTC).

Site 204

Latitude:	53° 34.0' N	Gravity Core (GC):	10x172 cm
Longitude:	98° 06.3' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.8 m asl, 15.9 m	Piston (Split) Core (PC):	10x579 cm
Date (Julian):	237/1814 (GC) and 237/1837 (PC)	PC Apparent Penetration:	922 cm

Lithology:



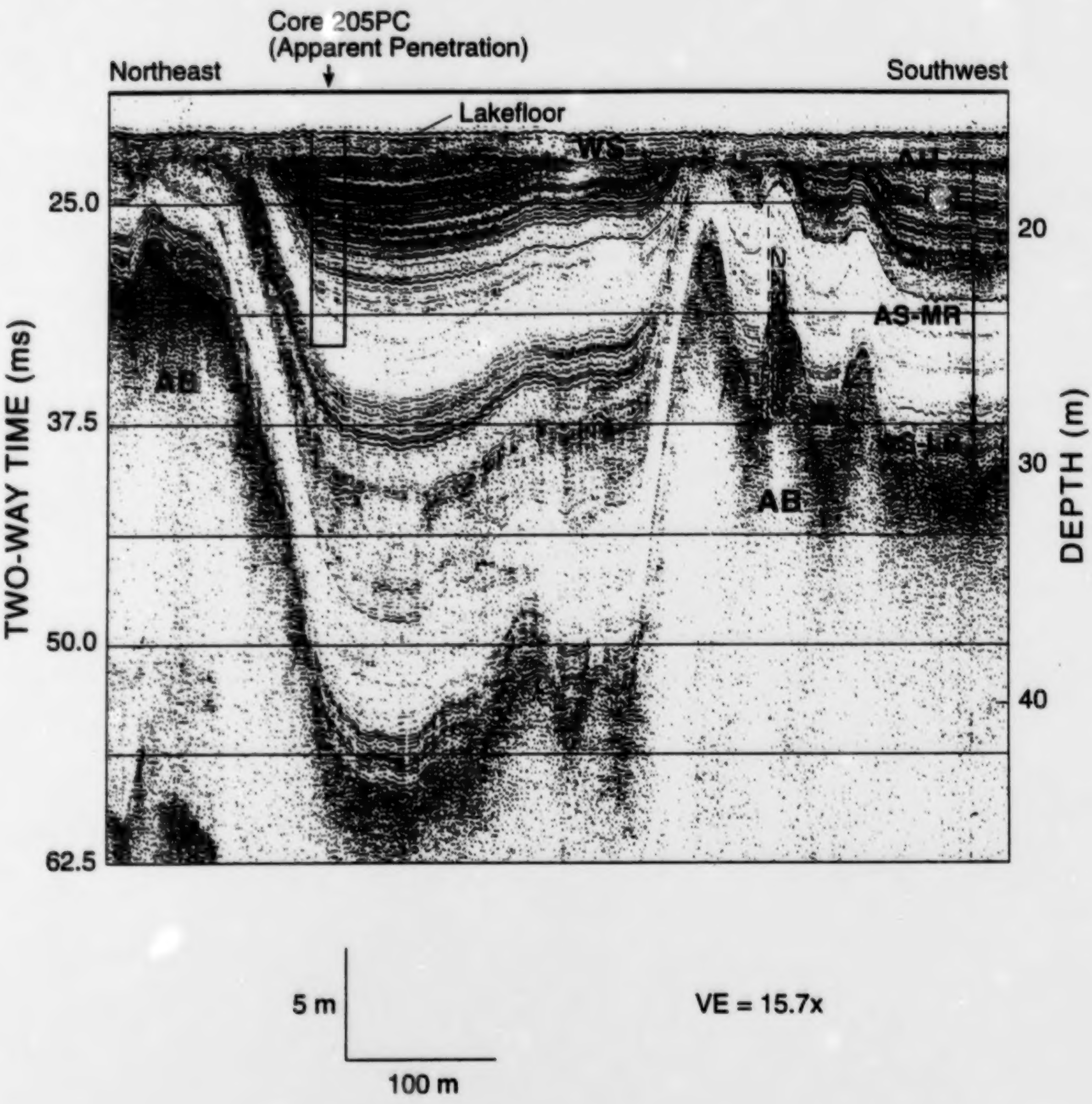
0-28 cm (GC)	**Silty-clay mud;** very soft, dark gray (5Y4/1), massive. Noncalcareous, with 0.3 cm surface oxidized unit. Black FeS staining common 0.3-0.8 cm.
28-172 cm	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Massive with rare zones of diffuse banding and mm-scale lamination (131-134 cm).
0-30 cm (PC)	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Massive with rare black FeS specks. Gradational to next unit.
30-110 cm	**Clay mud;** soft, dark gray (5Y4/1), noncalcareous. Massive to faintly laminated. Scattered black FeS spotting.
110-330 cm	**Clay mud;** soft, dark gray (5Y4/1), noncalcareous. Diffusely banded and mottled intermittently below 110 cm.
330 cm	**Contact;** faint.
330-579 cm	**Silty clay mud and silt;** soft, dark gray (5Y4/1), calcareous. Scattered pods and lenticular mm-scale units of silt. Occasional sharp-based laminae of silt and fine sand, becoming more frequent downcore, especially below 450 cm. At 362-373 cm, ostracodes dated 6700±80 (CAMS 38676). At 513-518 cm, a spruce needle fragment dated 6750±70 (CAMS38678).

Core intervals equivalent to seismostratigraphic sequences:

0-579? cm Winnipeg Sequence (Lake Winnipeg sediments).

Summary lithologic log for cores 204GC and 204PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 205



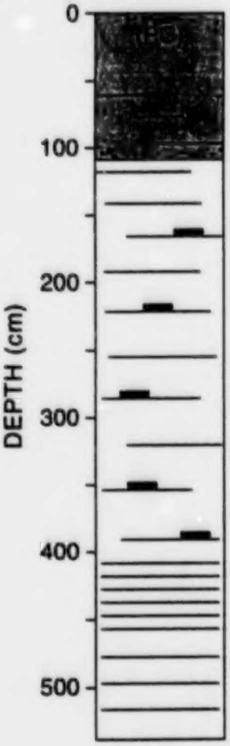
High resolution seismic reflection (Seistec) profile near core site 205 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence (AS), UR = Upper Reflective Interval, MR = Middle Reflective Interval, LR = Lower Reflective Interval. (Seistec record, line NB9, Day 229, 1994, 1250 UTC).

Site 205

Latitude: 53° 34.8' N
Longitude: 98° 04.8' W
Lake Level, Depth: 217.8 m asl, 15.9 m
Date (Julian): 238/1739 (GC) and 238/1819 (PC)

Gravity Core (GC): 10x162 cm
GC Apparent Penetration: 190 cm
Piston (Split) Core (PC): 10x537 cm
PC Apparent Penetration: 886 cm

Lithology:



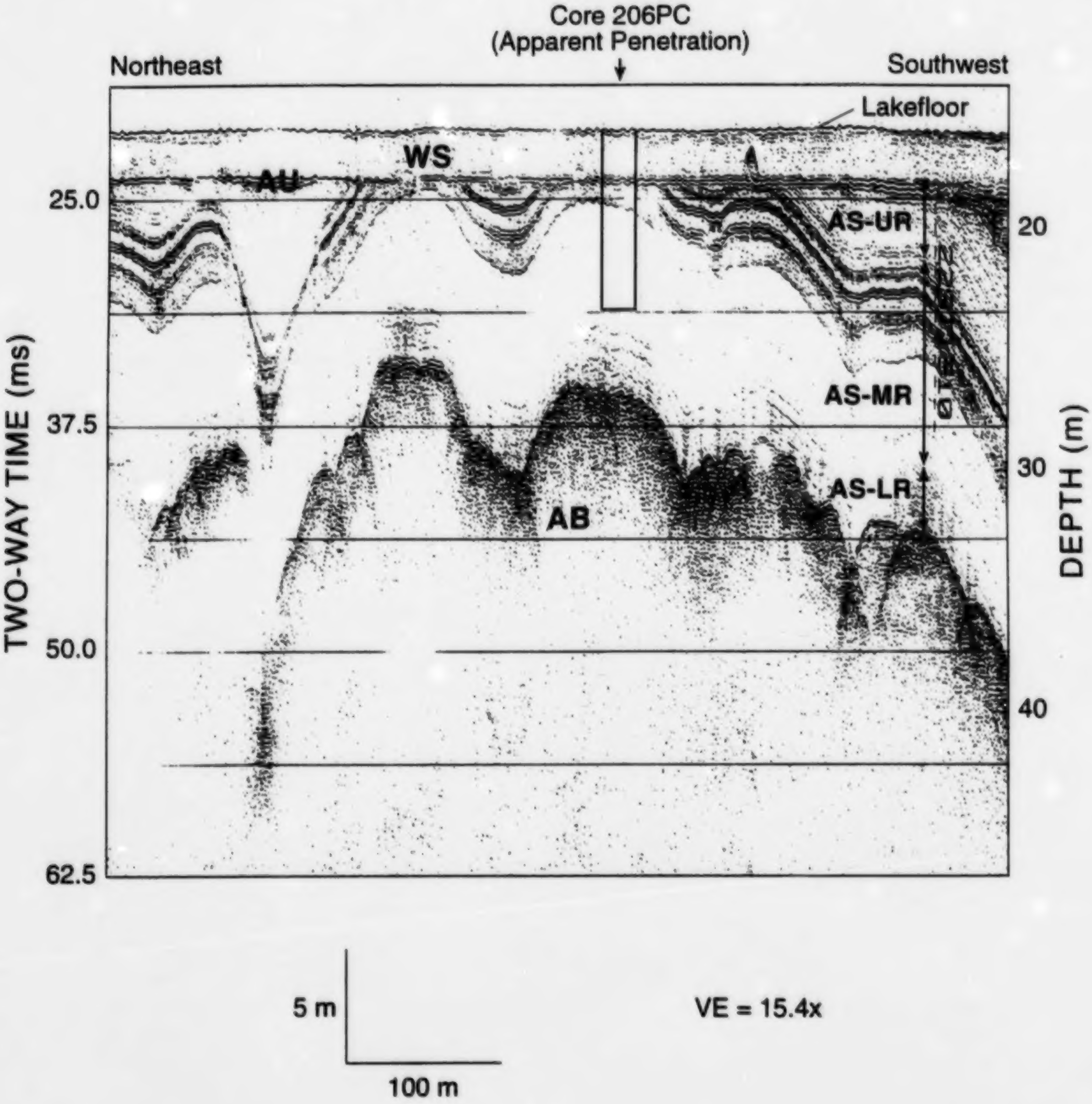
0-24 cm (GC)	**Silty clay mud;** very soft, dark olive gray (5Y3/2). Noncalcareous, banded to diffusely faintly laminated. Prominent bands of black FeS staining in upper 24 cm.
24-152 cm	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Very faintly diffusely laminated to mottled. Little black FeS staining, possibly burrowed. Grades to unit below.
152-162 cm	**Mud and sand;** soft, dark gray (5Y4/1) silty clay mud and gray (5Y5/1) finely laminated sand. Calcareous.
0-60 cm (PC)	**Silty clay mud;** soft, dark gray (5Y4/1), massive to faintly laminated and mottled, with some black FeS staining. Noncalcareous. Conformable transition to unit below.
60-107 cm	**Mud and sand;** soft, dark gray (5Y4/1) silty clay mud and pods, lenses, and fine laminae of silt and fine sand. Calcareous.
107 cm	**Contact;** conformable.
107-407 cm	**Silty clay;** soft-firm, diffusely, finely laminated, gray (10YR5/1) and light olive gray (5Y6/2) with occasional silt laminations. Calcareous. Grades to unit below, lighter laminae becoming thicker.
407-465 cm	**Silty clay;** soft to firm, thin mm-scale rhythmites. Sharp-based light olive gray layers (in places silty) grading up to darker gray layers comprise mm-scale couplets. Grades to unit below, lighter layers becoming thicker.
465-537 cm	**Silty clay;** firm, thick, cm-scale rhythmites. Sharp-based, light olive gray (5Y5/2), laminated layers (laminae silty in places) grade up to uniform darker (grayish-brown - 2.5Y5/2- to gray - 5Y3/2) layers in couplets that thicken downcore to 7 cm at base. Microfaulting throughout core probably due to faulty corer action.

Core intervals equivalent to seismostratigraphic sequences:

0-107 cm	Winnipeg Sequence.
107-537 cm	Agassiz Sequence.

Summary lithologic log for cores 205GC and 205PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 206

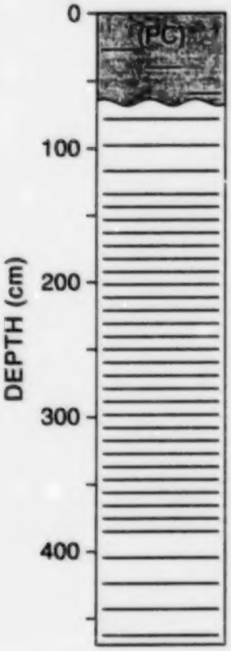


High resolution seismic reflection (Seistec) profile near core site 206 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence (AS), UR = Upper Reflective Interval, MR = Middle Reflective Interval, LR = Lower Reflective Interval. (Seistec record, line NB9, Day 229, 1994, 1310 UTC).

Site 206

Latitude:	53° 34.6' N	Gravity Core (GC):	10x168 cm
Longitude:	98° 05.3' W	GC Apparent Penetration:	190 cm
Lake Level, Depth:	217.8 m asl, 15.9 m	Piston (Split) Core (PC):	10x469 cm
Date (Julian):	238/1909 (GC) and 238/1938 (PC)	PC Apparent Penetration:	732 cm

Lithology:



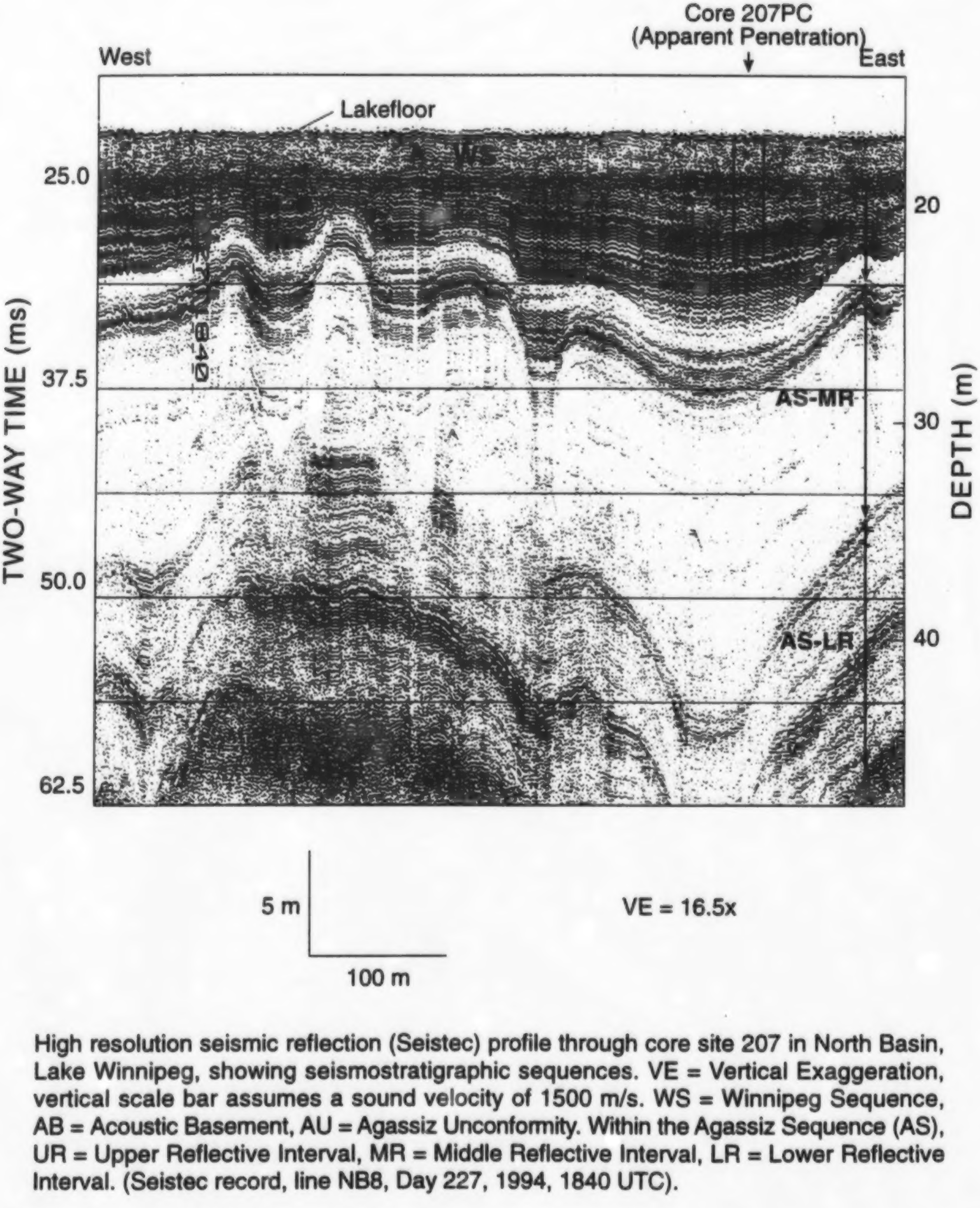
0-168 cm (GC)	**Silty clay mud;** very soft, dark olive gray (5Y3/2). Noncalcareous. Massive to faintly mottled. Diffusely to clearly laminated 20-40 cm. Diffusely banded 88-106 cm.
0-60 cm (PC)	**Silty clay mud;** soft, gray to dark gray (5Y5/1 - 5Y4/1). Noncalcareous. Dark grayish brown (10YR4/2) surface oxidized layer 0-0.5 cm. Indistinct laminations and banding 0.5-28 cm. Massive with incipient mottling and black specks 28-60 cm.
60-69 cm	**Silty clay mud;** soft, gray (5Y5/1), faint cm-scale banding.
69 cm	**Contact;** sharp, irregular, erosional.
69-134 cm	**Silty clay;** soft-firm, thick cm-scale rhythmites, calcareous. Sharp-based, lighter gray (5Y4/1) laminated layers grade up to uniform, darker gray (5Y4/2) layers. Rhythmite couplets thin downcore from 5 cm at top of unit, becoming sub cm-scale below 116 cm. Grades to unit below.
134-387 cm	**Clay;** firm, thin mm-scale rhythmites, 2-4 couplets per cm with thicker lighter layers at ~10 cm intervals. Calcareous. Sharp-based, lighter dark gray (5Y4/1) layers grading up to darker olive gray (5Y4/2) layers comprise the couplets. Browner (10YR5/1) and thicker layers below 312 cm. Grades to unit below.
387-469 cm	**Silty clay;** firm, thick, medium sub cm-scale rhythmites. Calcareous. Similar to unit above with thicker, lighter, gray (5Y5/1) clay layers; in places, lighter layers contain additional lighter silt laminae, light gray (5Y6/1). Couplets thicken downcore to 1-2 per cm. Below 450 cm, darker layers within couplets become more dominant.

Core intervals equivalent to seismostratigraphic sequences:

0- 69 cm	Winnipeg Sequence (Lake Winnipeg sediments).
69-469 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 206GC and 206PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 207

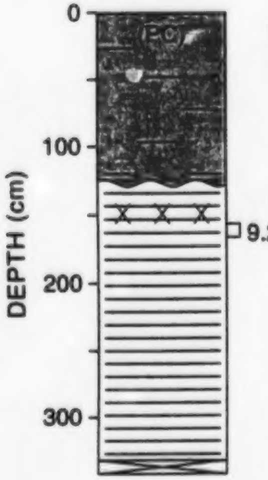


High resolution seismic reflection (Seistec) profile through core site 207 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence (AS), UR = Upper Reflective Interval, MR = Middle Reflective Interval, LR = Lower Reflective Interval. (Seistec record, line NB8, Day 227, 1994, 1840 UTC).

Site 207

Latitude:	52° 51.6' N	Gravity Core (GC):	10x174 cm
Longitude:	97° 51.2' W	GC Apparent Penetration:	175 cm
Lake Level, Depth:	217.7 m asl, 17.1 m	Piston (Split) Core (PC):	10x344 cm
Date (Julian):	239/1425 (GC) and 239/1455 (PC)	PC Apparent Penetration:	540 cm

Lithology:



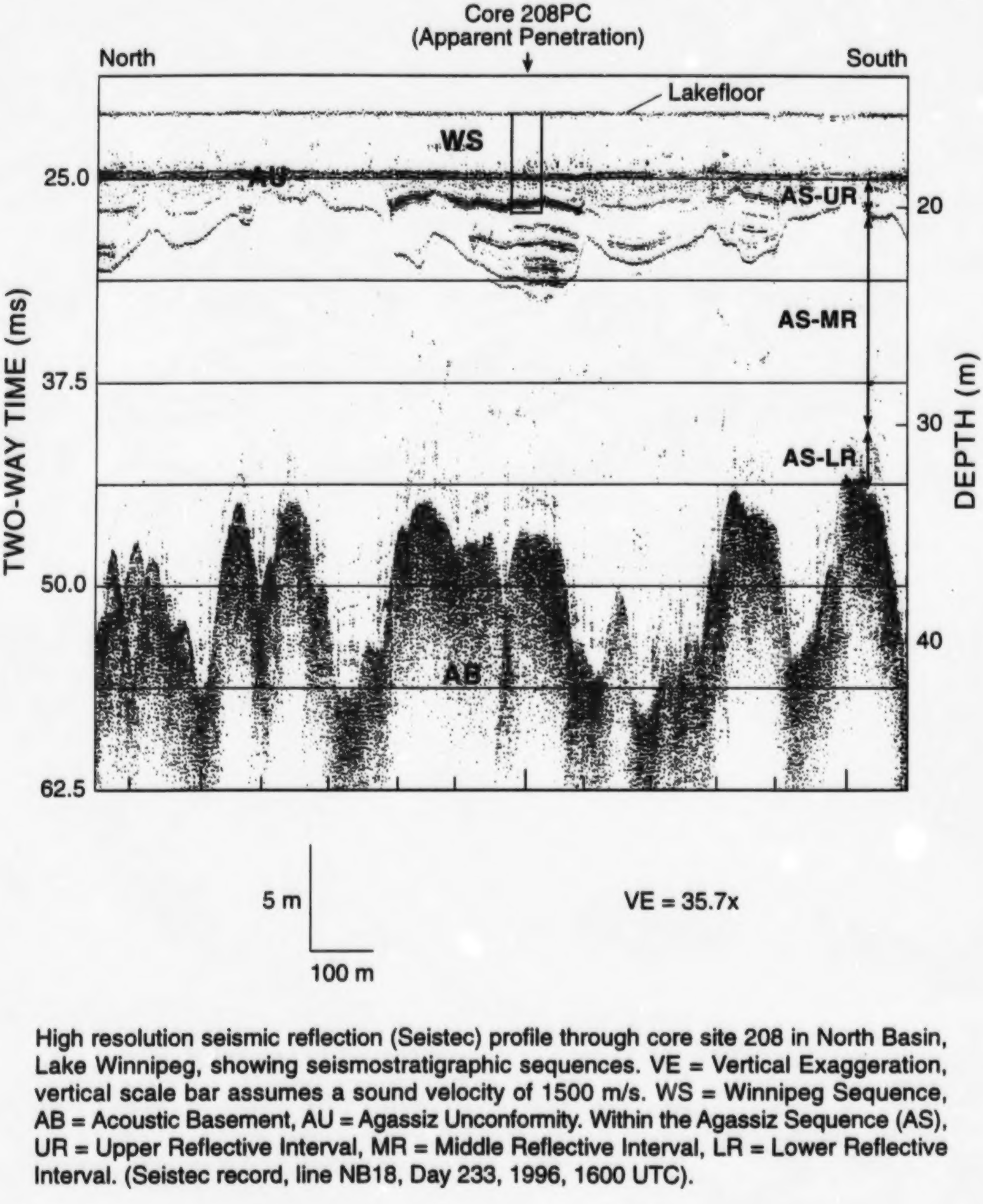
0-174 cm (GC)	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Surface olive brown (2.5Y4/4) oxidized layer 0-0.4 cm, over black FeS-stained (5Y3/1) layer 0.4-1.5 cm. Faintly diffusely laminated and mottled with black FeS specks and scattered occurrences of lighter gray laminations and lenses.
0-124 cm (PC)	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Black FeS-streaked in upper 8 cm. Faintly mottled, diffusely laminated, with lighter gray mud.
124 cm	**Contact;** sharp.
124-334 cm	**Silty clay;** stiff, dark gray to gray (5Y4/1). Weakly calcareous. Faintly laminated and conchoidally fractured (crumbly) to ~160 cm. Below ~160 cm, becomes gradationally softer (firm), noncalcareous, rhythmically laminated with repetitive sets of sharp-based (silt) fining-upward layers. At 155-163 cm, ostracodes dated 9170±70 (CAMS 38677).
334-344 cm	Recored material

Core intervals equivalent to seismostratigraphic sequences:

0-124 cm	Winnipeg Sequence (Lake Winnipeg sediments).
124-334 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 207GC and 207PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 208

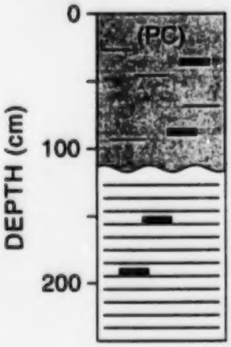


High resolution seismic reflection (Seistec) profile through core site 208 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence (AS), UR = Upper Reflective Interval, MR = Middle Reflective Interval, LR = Lower Reflective Interval. (Seistec record, line NB18, Day 233, 1996, 1600 UTC).

Site 208

Latitude:	52° 41.2' N	Gravity Core (GC):	10x165 cm
Longitude:	97° 37.3' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.7 m asl, 15.6 m	Piston (Split) Core (PC):	10x244 cm
Date (Julian):	239/1740 (GC) and 239/1803 (PC)	PC Apparent Penetration:	450 cm

Lithology:

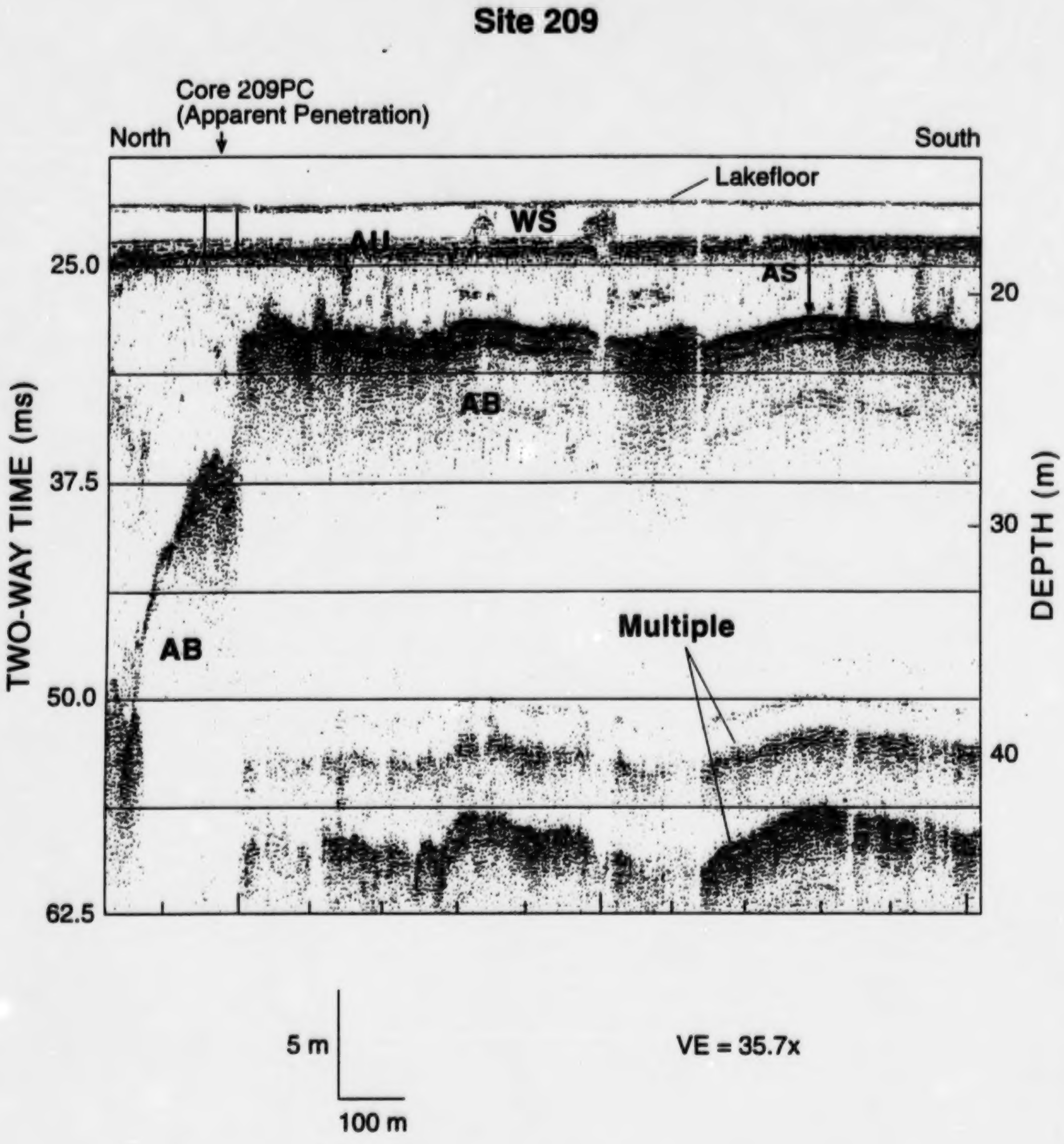


0-165 cm (GC)	**Silty clay mud;** soft, noncalcareous. Massive surface layer, dark olive gray (5Y3/2), 0-3 cm; massive also 81-87 cm. Faintly, diffusely laminated 1-10 mm, olive gray (5Y4/2) and lighter (5Y4/2), 3-54 cm, with scattered FeS staining, 3-12 cm. Regular olive gray (5Y4/2) laminae, 15±5 mm, and paler olive gray, <0.5-5 mm, laminae, 54-81 cm. Finely, distinctly laminated, 87-126 cm, wavy, flute-like cross-cutting in places. Faintly, diffusely, irregularly laminated and locally bioturbated (burrowed), 126-165 cm.
0-116 cm (PC)	**Silty clay mud;** soft, noncalcareous, mainly dark gray (5Y3/1). Massive olive gray (5Y4/3) surface layer, 0-1.5 cm. Irregularly spaced laminations with black speckling, 1.5-21 cm. Wavy laminations with occasional silt partings, 21-60 cm. Faintly, diffusely laminated, 60-116 cm, with occasional silt lenses and partings, especially 85-90 cm.
116 cm	**Contact;** abrupt.
116-244 cm	**Silty clay;** stiff, dark gray (5Y4/1), calcareous. Finely laminated throughout with olive gray (5Y5/2) lenticular silt laminae, common 155-180 cm.

Core intervals equivalent to seismostratigraphic sequences:

0-116 cm	Winnipeg Sequence (Lake Winnipeg sediments).
116-244 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 208GC and 208PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

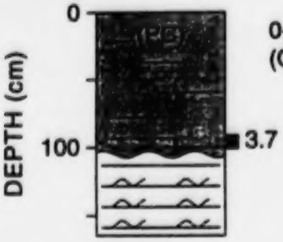


High resolution seismic reflection (Seistec) profile through core site 209 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line NB18, Day 233, 1996, 1600 UTC).

Site 209

Latitude:	52° 30.9' N	Gravity Core (GC):	10x173 cm
Longitude:	97° 34.8' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.7 m asl, 16.5 m	Piston (Split) Core (PC):	10x165 cm
Date (Julian):	239/1949 (GC) and 239/2011 (PC)	PC Apparent Penetration:	213 cm

Lithology:



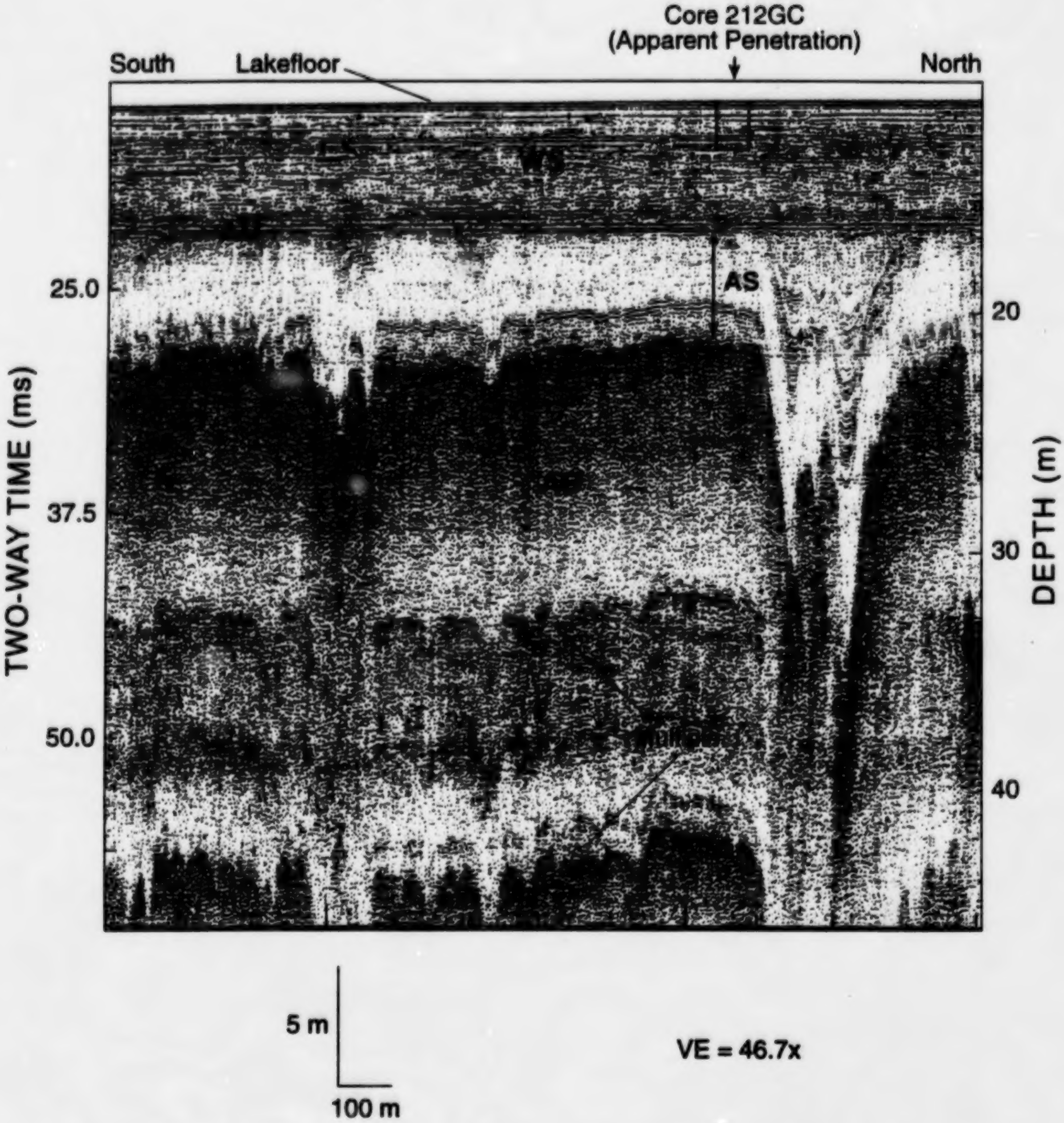
0-173 cm (GC)	**Silty clay mud;** soft, noncalcareous. Massive to mottled dark gray (5Y4/1) with thin 0.5 cm olive gray (5Y4/3) surface layer, and black FeS specks 0-12 cm. Diffusely, irregularly banded very dark gray (5Y3/1) and noncalcareous 12-22 cm. Finely laminated olive gray (5Y4/2), 22-116 cm, with complex cyclic structure and small-scale unconformities; laminae vary <1-8 mm in cycles 20-25 mm. Dark olive gray (5Y3/2) and dark gray (5Y4/1) banded and noncalcareous 116-128 cm. Disturbed structures, irregular blebs, discontinuous and contorted laminae, mottling 128-173 cm.
0-95 cm (PC)	**Silty clay mud;** soft, olive gray (5Y4/2), noncalcareous. Surface oxidized layer (2.5Y4/1) 0-1 cm. Otherwise laminated (<1-10 mm) becoming diffuse below 70 cm and contorted to massive below 80 cm.
95-104 cm	**Silt;** dark gray (5Y4/1), noncalcareous. Crudely stratified dark olive gray (5Y3/2) with plant fossils. At 95-97 cm, a juniper seed dated 3730±70 (CAMS 35497).
104 cm	**Contact;** sharp, erosional.
104-165 cm	**Silty clay;** very stiff, dark gray (10YR4/1), calcareous. Fine laminations disturbed 107 cm to base.

Core intervals equivalent to seismostratigraphic sequences:

0-104 cm	Winnipeg Sequence (Lake Winnipeg sediments).
104-165 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 209GC and 209PC correlated to seismostratigraphic sequences, northern Lake Winnipeg

Site 212

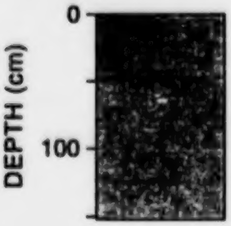


High resolution seismic reflection (Seistec) profile through core site 212 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line NB16, Day 228, 1996, 1815 UTC).

Site 212

Latitude:	52° 03.1' N	Gravity Core (GC):	10x153 cm
Longitude:	97° 04.1' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.8 m asl, 11.0 m	Piston Core (PC):	not taken
Date (Julian):	240/1611 (GC)		

Lithology:



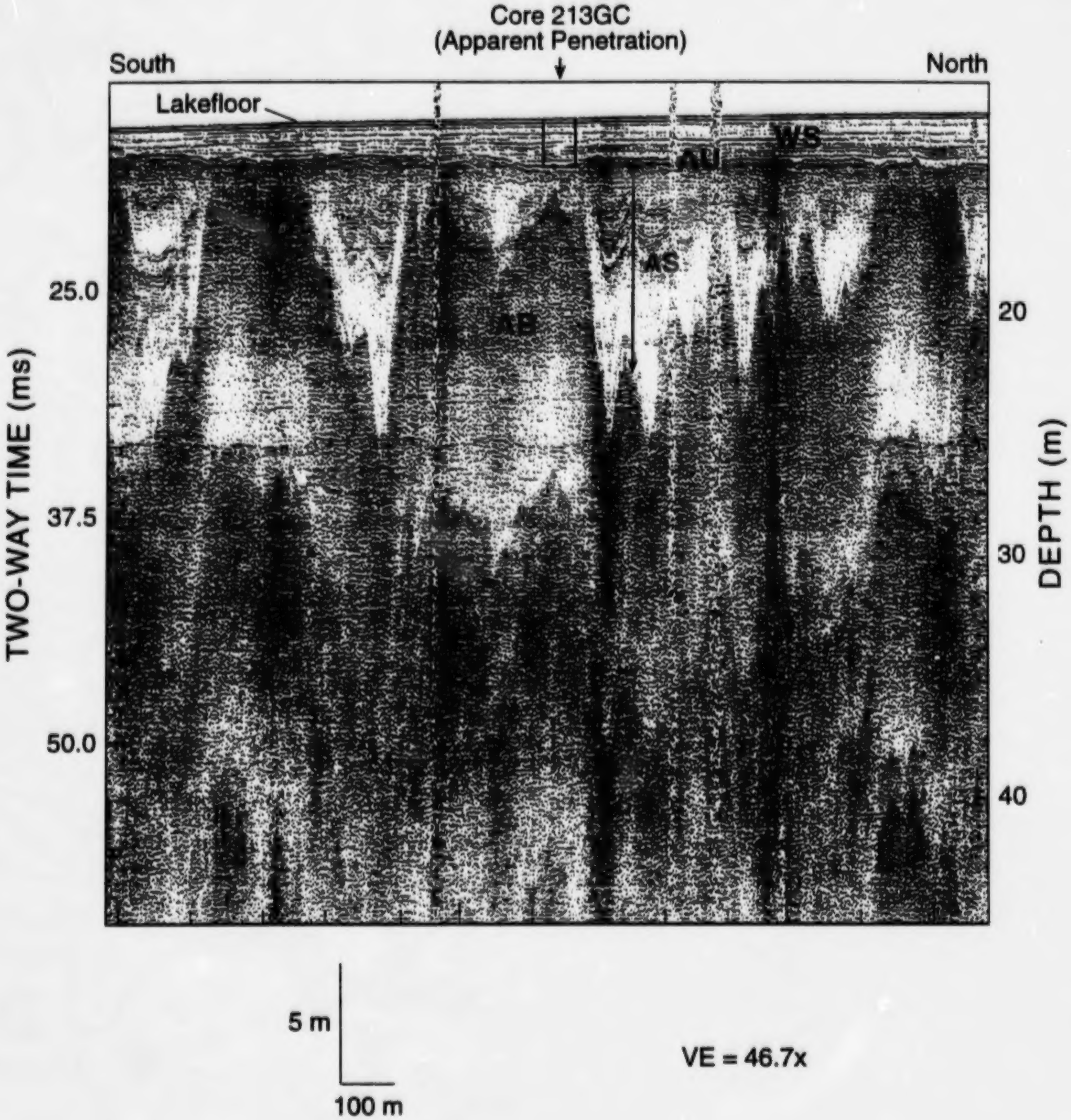
0-153 cm (GC)	**Silty clay mud;** soft, gray (5Y5/1), noncalcareous. Mostly massive with scattered lenses and balls of distorted paler gray mud. Small black fibres scattered throughout.

Core intervals equivalent to seismostratigraphic sequences:

0-153 cm Winnipeg Sequence (Lake Winnipeg sediments).

Summary lithologic log for core 212GC correlated to seismostratigraphic sequences, central Lake Winnipeg

Site 213

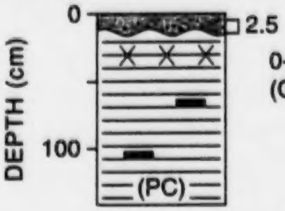


High resolution seismic reflection (Seistec) profile through core site 213 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line NB16, Day 228, 1996, 1525 UTC).

Site 213

Latitude:	51° 52.4' N	Gravity Core (GC):	10x161 cm
Longitude:	96° 56.5' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.8 m asl, 11.5 m	Piston (Solid) Core (PC):	10x143 cm
Date (Julian):	240/1745 (GC) and 240/1823 (PC)	PC Apparent Penetration:	150 cm

Lithology:



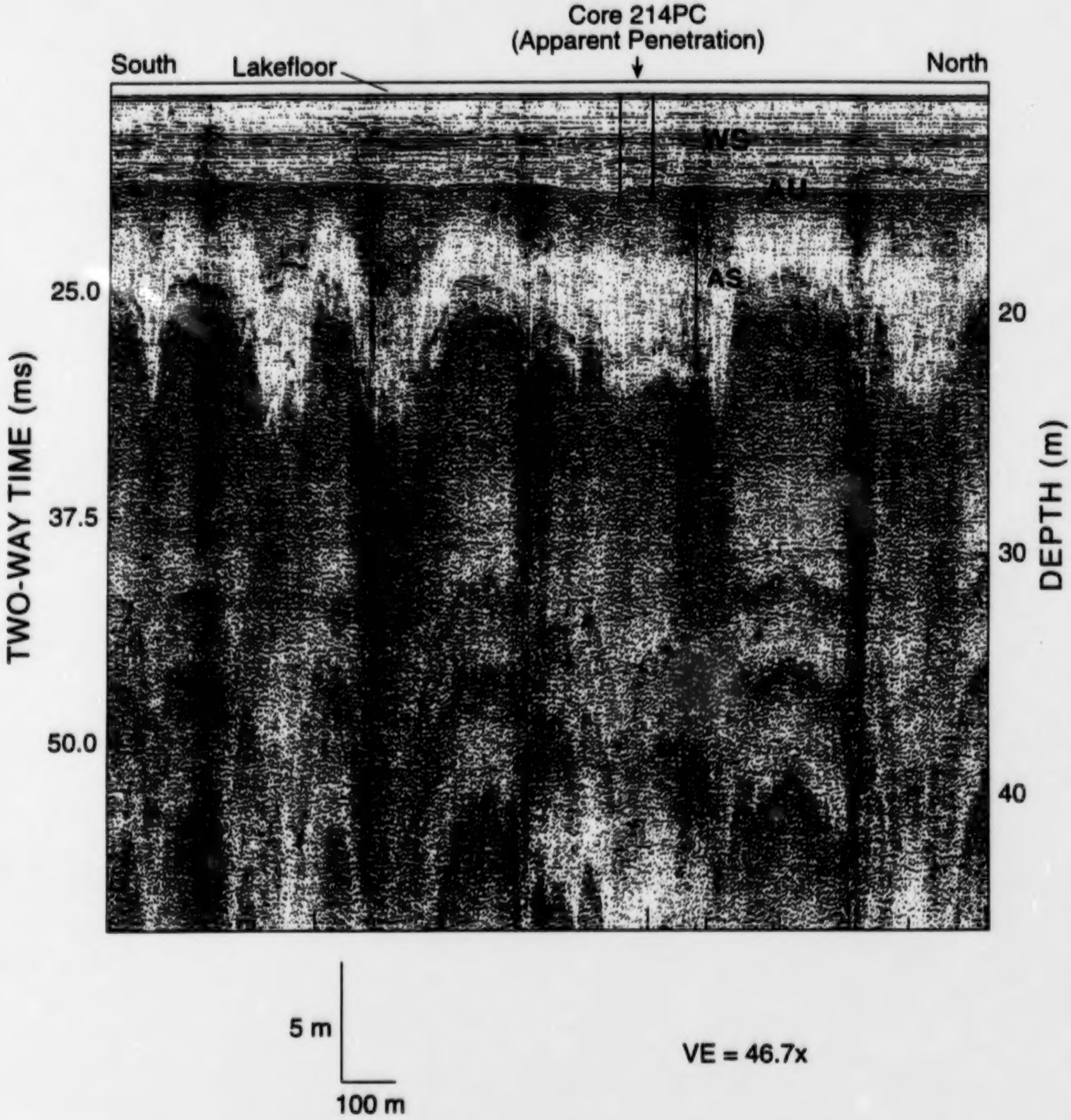
0-161 cm (GC)	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Very soft, dark grayish brown surface layer, 0-0.5 cm. Massive with incipient and distorted fine laminae or mottles of paler gray mud. Black specks and organic fibres throughout.
0-15 cm (PC)	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Thin (0.5 cm) surface oxidized (10YR4/2) layer. Massive with black specks. At 10-15 cm a spruce needle dated 2540±60 (CAMS 46187).
15 cm	**Contact;** sharp with trace of grit.
15-143 cm	**Clay;** stiff, dark gray (5Y4/1)-10YR4/1), calcareous. Fractured, irregular surface and noncalcareous in upper ~30 cm. Finely laminated with traces of silt; ~5-6 laminae/cm; thin rhythmites?

Core intervals equivalent to seismostratigraphic sequences:

0- 15 cm	Winnipeg Sequence (Lake Winnipeg sediments).
15-143 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 213GC and 213PC correlated to seismostratigraphic sequences, central Lake Winnipeg

Site 214

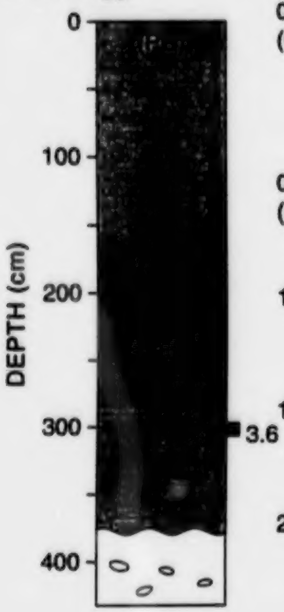


High resolution seismic reflection (Seistec) profile through core site 214 in North Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line NB16, Day 228, 1996, 1625 UTC).

Site 214

Latitude:	51° 56.1' N	Gravity Core (GC):	10x175 cm
Longitude:	96° 59.1' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.8 m asl, 11.3 m	Piston (Solid) Core (PC):	10x433 cm
Date (Julian):	240/1921 (GC) and 240/1938 (PC)	PC Apparent Penetration:	457 cm

Lithology:



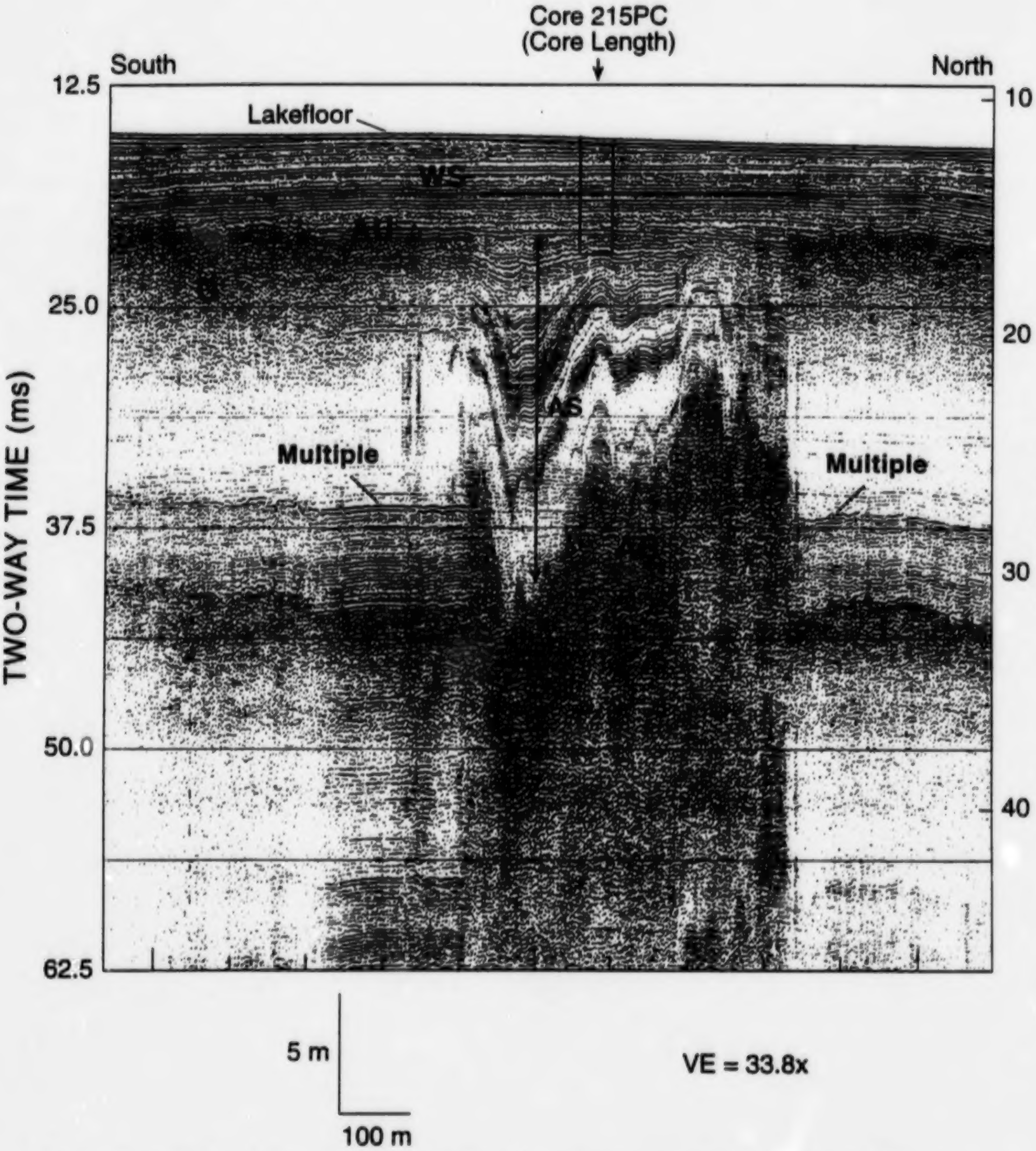
0-175 cm (GC)	**Silty clay mud;** soft, dark gray (5Y3/2), noncalcareous. Soupy, very soft surface. Concentrated black FeS staining, 5-6 cm. Massive to very faintly mottled, locally black specked. Occasional gray (5Y5/1) bands and fragments of laminae. Scattered wood, plant and other organic fragments.
0-140 cm (PC)	**Silty clay mud;** soft, dark olive gray (5Y3/2). Massive to gray mottled, rarely diffusely banded with disseminated fine black organic flecks. Grades to unit below.
140-176 cm	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous. Contorted gray (5Y5/1) laminations and burrows. Disseminated fine black organics. Grades to unit below.
176-220 cm	**Silty clay mud;** soft, gray (5Y5/1), noncalcareous. Faintly, diffusely laminated, mottled and burrowed with scattered black organic fragments. Very gradational to unit below.
220-375 cm	**Silty clay mud;** soft, dark gray (5Y4/1), noncalcareous; otherwise as in 176-220 cm. Occasional gray (5Y5/1) clay bands and darker laminae with black organic fragments, also dark gray (5Y4/1) silt band, 302-303 cm. Becoming olive gray (5Y5/2) below 305 cm, diffusely laminated, mottled and burrowed. Distinct bands, contorted in places, of gray (5Y5/1) mud. At 298-303 cm, a wood fragment dated 3630±375 (CAMS 38679).
375 cm	**Contact;** abrupt, erosional.
375-425 cm	**Clayey silt;** firm to stiff, dark gray (5Y4/1), calcareous. Sticky, blocky texture to about 397 cm. Black mottled with white calcite concretions and dropstones becoming more frequent below 408 cm. Limestone pebble (1 cm) at 421.5 cm
425-433 cm	Recored material, blocky clayey silt from 375 cm and below.

Core intervals equivalent to seismostratigraphic sequences:

0-375 cm	Winnipeg Sequence (Lake Winnipeg sediments).
375-425 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 214GC and 214PC correlated to seismostratigraphic sequences, central Lake Winnipeg

Site 215

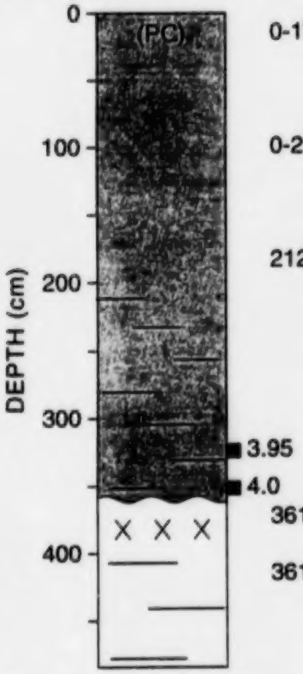


High resolution seismic reflection (Seistec) profile through core site 215 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. G = gas masking, WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line SB15, Day 227, 1996, 1945 UTC).

Site 215

Latitude:	51° 22.5' N	Gravity Core (GC):	10x173 cm
Longitude:	96° 34.3' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	218.1 m asl, 11.6 m	Piston (Solid) Core (PC):	10x485 cm
Date (Julian):	241/1617 and 1638	PC Apparent Penetration:	320 cm

Lithology:



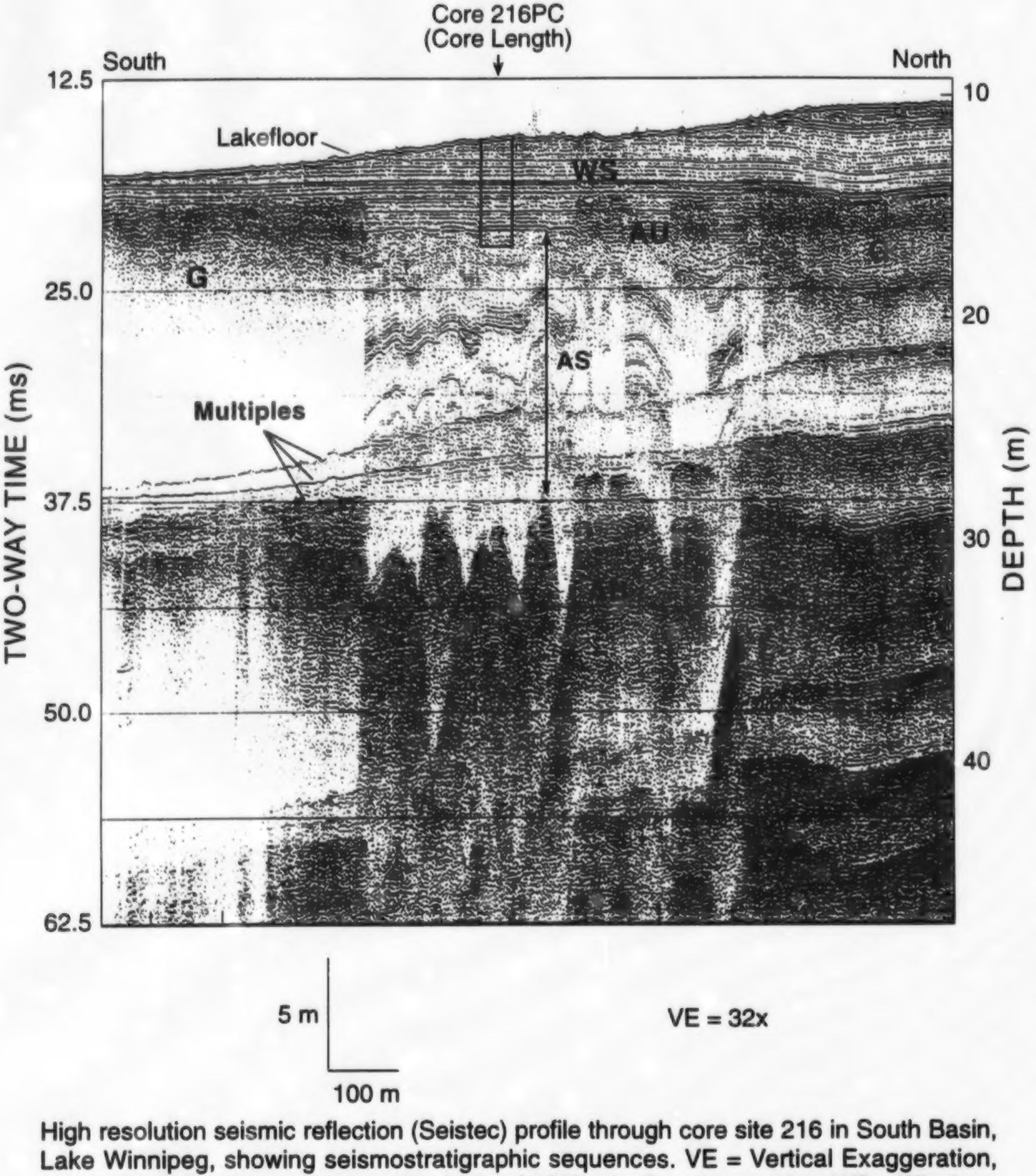
0-173 cm (GC)	**Silt-clay mud;** soft, olive gray (5Y4/2), noncalcareous. Diffusely mottled with black FeS? staining. Gray (5Y5/1), mottled with hint of lamination below about 50 cm
0-212 cm (PC)	**Silt-clay mud;** soft, dark gray (5YR4.5/1), faintly mottled or burrowed, black FeS? streaked. Noncalcareous. Rare organic fragments and disseminated organics.
212-361 cm	**Silt-clay mud;** soft, crudely stratified, dark gray with silt interbeds, widespread plant detritus and scattered shells / shell fragments. Noncalcareous. At 331-348 cm, almost rhythmically bedded (mm-scale) dark and lighter gray (all 5Y4/1) silt-clay mud. At 321.5 cm, *Scirpus* seed dated 3950±60 (CAMS 34554). At 348 cm, *Scirpus* seed dated 4030±50 (CAMS 34555).
361 cm	**Contact;** erosional, sharp.
361-485 cm	**Clay;** firm, crumbly in silt-sand sized fragments, dark gray (5Y4/1). Highly calcareous. Scattered shell fragments. Vertical black organic stains (root casts?) to 380 cm. Black zones 1-6 cm thick 412-434 cm. Light olive brown zone (2.5Y5/4) 434-440 cm over cm-thick olive to black zones, then dark gray (5Y5/1) to base.

Core intervals equivalent to seismostratigraphic sequences:

0-361 cm	Winnipeg Sequence (Lake Winnipeg sediments).
361-485 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 215GC and 215PC correlated to seismostratigraphic sequences, central Lake Winnipeg

Site 216

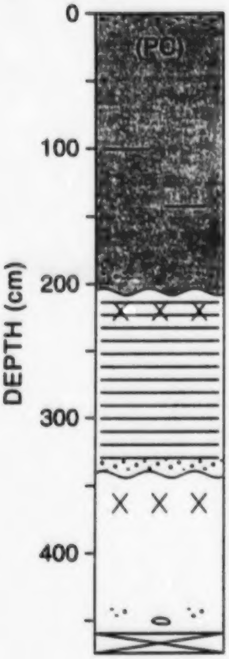


High resolution seismic reflection (Seistec) profile through core site 216 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. G = gas masking, WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line SB15, Day 227, 1996, 1755 UTC).

Site 216

Latitude:	51° 17.1' N	Gravity Core (GC):	10x113 cm
Longitude:	96° 37.8' W	GC Apparent Penetration:	120 cm
Lake Level, Depth:	218.1 m asl, 11.9 m	Piston (Solid) Core (PC):	10x475 cm
Date (Julian):	241/1740 and 1845	PC Apparent Penetration:	457 cm

Lithology:



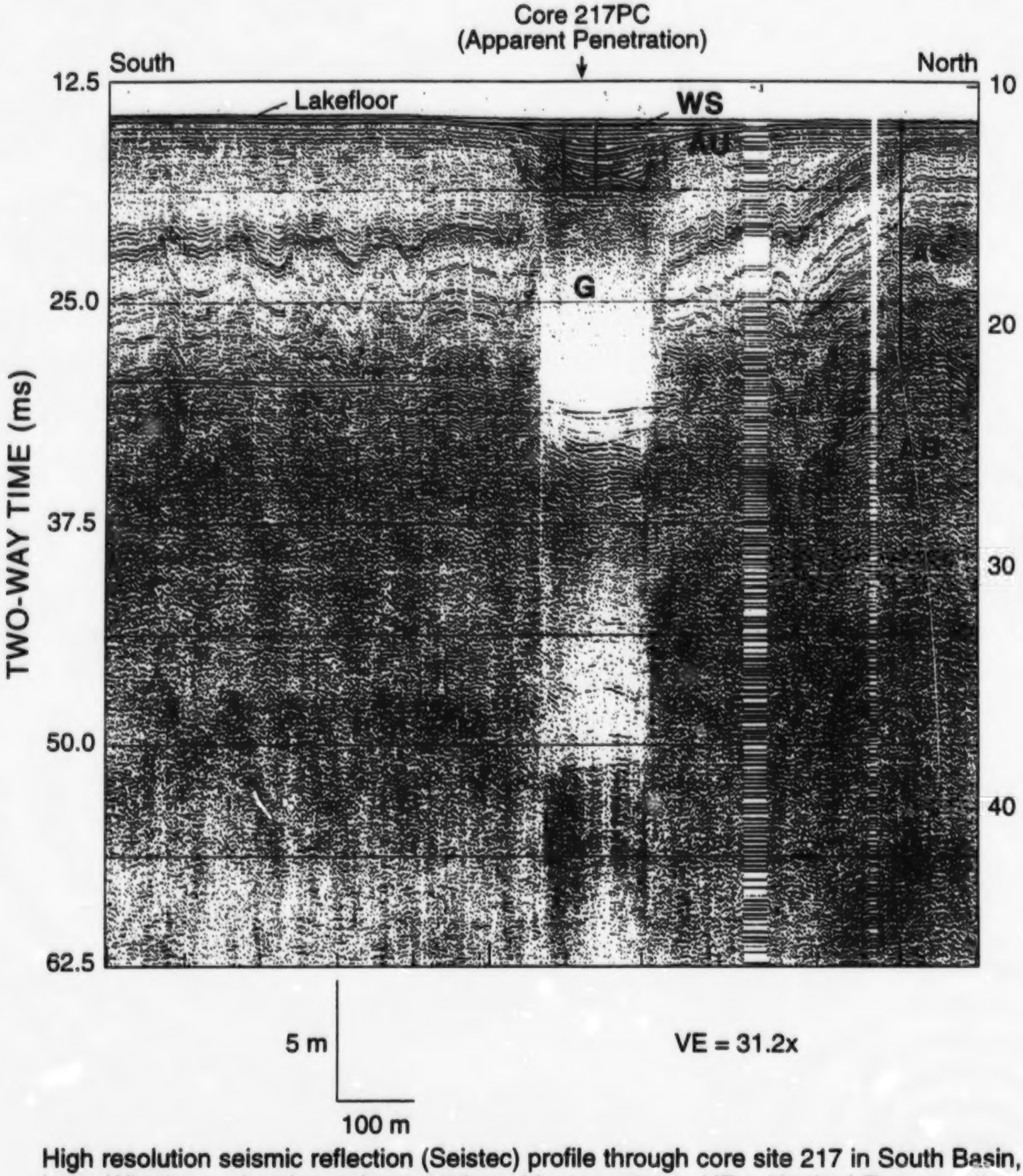
0-4 cm (GC)	**Muddy sand;** loose, gray (5Y5/1), noncalcareous with shale? pebbles. Dark grayish brown (10YR4/2) surface oxidized layer, 0-0.5 cm.
4 cm	**Contact;** sharp, erosional.
4-113 cm	**Silty clay mud;** soft, dark gray to gray (5Y4.5/1), noncalcareous. Massive with black speckling and rare, faintly banded to mottled zones. Organic fragment at 50 cm.
0-4 cm (PC)	**Muddy sand;** loose with pebble, dark olive gray (5Y3/2), noncalcareous. Very soft, dark grayish brown (10YR4/2), silty clay mud surface oxidized layer.
4-204 cm	**Silty clay mud;** soft, dark gray (5Y4.5/1). Noncalcareous, with black speckling and scattered organic fragments. Minor FeS (no H2S odour on application of HCl). Rarely faintly banded to mottled. Siltier interbeds 196 and 197 cm. Twig at 198 cm.
204 cm	**Contact;** sharp, erosional.
204-342 cm	**Silty clay;** firm, dark gray (5Y4/1), slightly blocky near upper contact. Faintly fine-laminated, more common below 315 cm, with contorted 'pancake' rippling. Noncalcareous. Silt interbed at 335 cm.
342 cm	**Contact;** sharp, erosional.
342-461 cm	**Silty clay;** stiff, crumbly, very dark gray (5Y3.8/1), with fine, black (organic?) fragments. Noncalcareous, becoming calcareous below 450 cm. Silt interbeds 345 and 346 cm. Pebble 450 cm.
461-475 cm	Recored mud.

Core intervals equivalent to seismostratigraphic sequences:

0-342 cm	Winnipeg Sequence (Lake Winnipeg sediments).
342-461 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 216GC and 216PC correlated to seismostratigraphic sequences, central Lake Winnipeg

Site 217

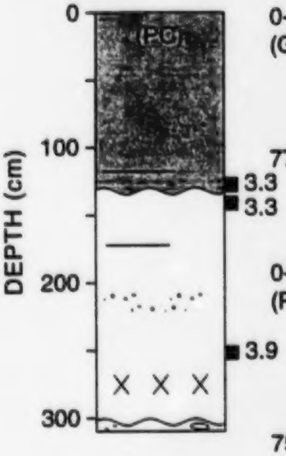


High resolution seismic reflection (Seistec) profile through core site 217 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. G = gas masking, WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line SB15, Day 227, 1996, 1500 UTC).

Site 217

Latitude:	51° 08.0' N	Gravity Core (GC):	10x109 cm
Longitude:	96° 35.1' W	GC Apparent Penetration:	120 cm
Lake Level, Depth:	218.1 m asl, 11.1 m	Piston (Solid) Core (PC):	10x310 cm
Date (Julian):	241/2000 and 2020	PC Apparent Penetration:	320 cm

Lithology:



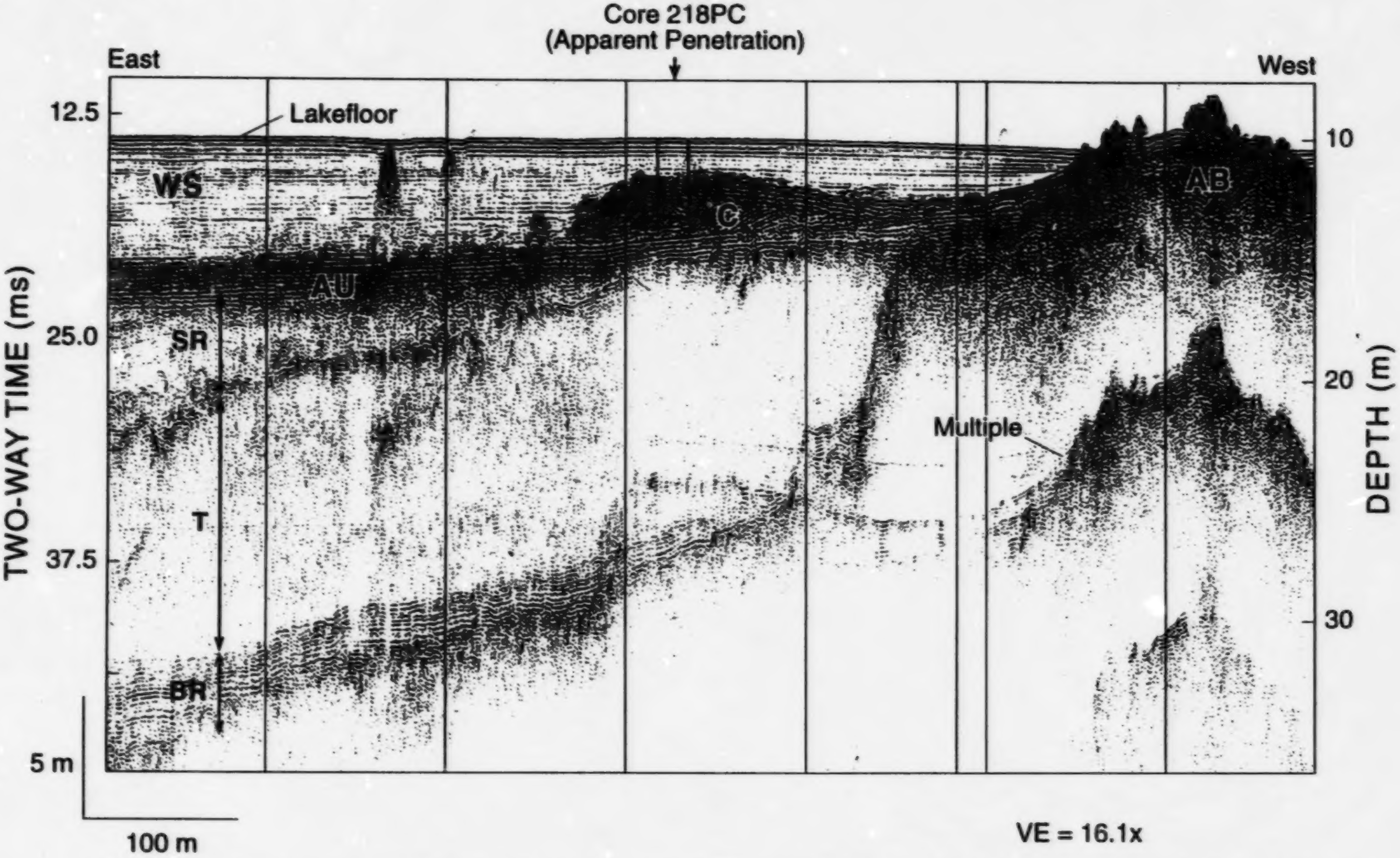
0-77 cm (GC)	**Silty clay mud;** soft, olive gray (5Y4/2), noncalcareous. Surface dark yellowish brown (10YR3/4) oxidized layer, 0-0.5 cm. Black staining prominent 8-12 and 63-68 cm. Diffusely laminated to mottled with burrows.
77-109 cm	**Silt-clay mud;** soft, gray (5Y4.5/1), noncalcareous. Diffusely, irregularly banded. Finely disseminated black organics throughout with plant macrofossils and wood at 98-99 cm.
0-75 cm (PC)	**Silty clay mud;** soft, olive gray (5Y4/2) to dark gray (5Y4/1), noncalcareous. Surface dark yellowish brown (10YR3/4) oxidized layer. Faintly and diffusely laminated to mottled with burrows. Black streaking (FeS?, organics?), especially 3-12, 20-23, and 67-75 cm, and sparsely throughout.
75-132 cm	**Silt-clay mud;** soft, gray (5Y5/1), noncalcareous. Rarely, faint mottling and, near base, incipient banding. Silt interbed, lenticular, calcareous 86.5 cm. Organic fragments in layers at 126 and 129 cm. At 127-132 cm, *Scirpus* seed dated 3340±50 (CAMS 35498).
132 cm	**Contact;** sharp, erosional.
132-302 cm	**Silty clay;** firm, crumbly, dark gray (5Y4/1) and gray (5Y4.5/1) below 266 cm. Noncalcareous to calcareous below 266 cm. Little apparent primary structure except for bedding 172 cm and muddy silt beds 207-209 and 211-213 cm. Large shell at 200 cm. At 135-140 cm, *Scirpus* seed dated 3340±40 (CAMS 46190). At 253-257 cm, *Chenopodium* sp. seeds dated 3910±60 (CAMS 46191).
302 cm	**Contact;** sharp, erosional.
302-310 cm	**Silty clay;** stiff, not crumbly, gray (5Y5/1). Weakly calcareous with calcareous silt lenses and balls of sand and granules.

Core intervals equivalent to seismostratigraphic sequences:

0-302? cm	Winnipeg Sequence (Lake Winnipeg sediments).
302?-310 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 217GC and 217PC correlated to seismostratigraphic sequences, southern Lake Winnipeg

Site 218

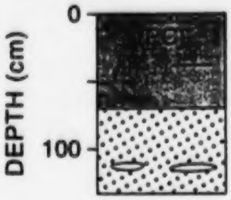


High resolution seismic reflection (Seistec) profile through core sites 218 and 219 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, C = Clinoforms, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence, SR = Segmented Reflective Interval, T = Transparent Interval, BR = Basal Reflective Interval. (Seistec record, Pearson Reef site survey, Day 242, 1996, 1608 UTC).

Site 218

Latitude:	50° 56.6' N	Gravity Core (GC):	not taken
Longitude:	96° 40.9' W	Piston (Solid) Core (PC):	10x139 cm
Lake Level, Depth:	217.8 m asl, 10.4 m	PC Apparent Penetration:	300 cm
Date (Julian):	242/1814		

Lithology:



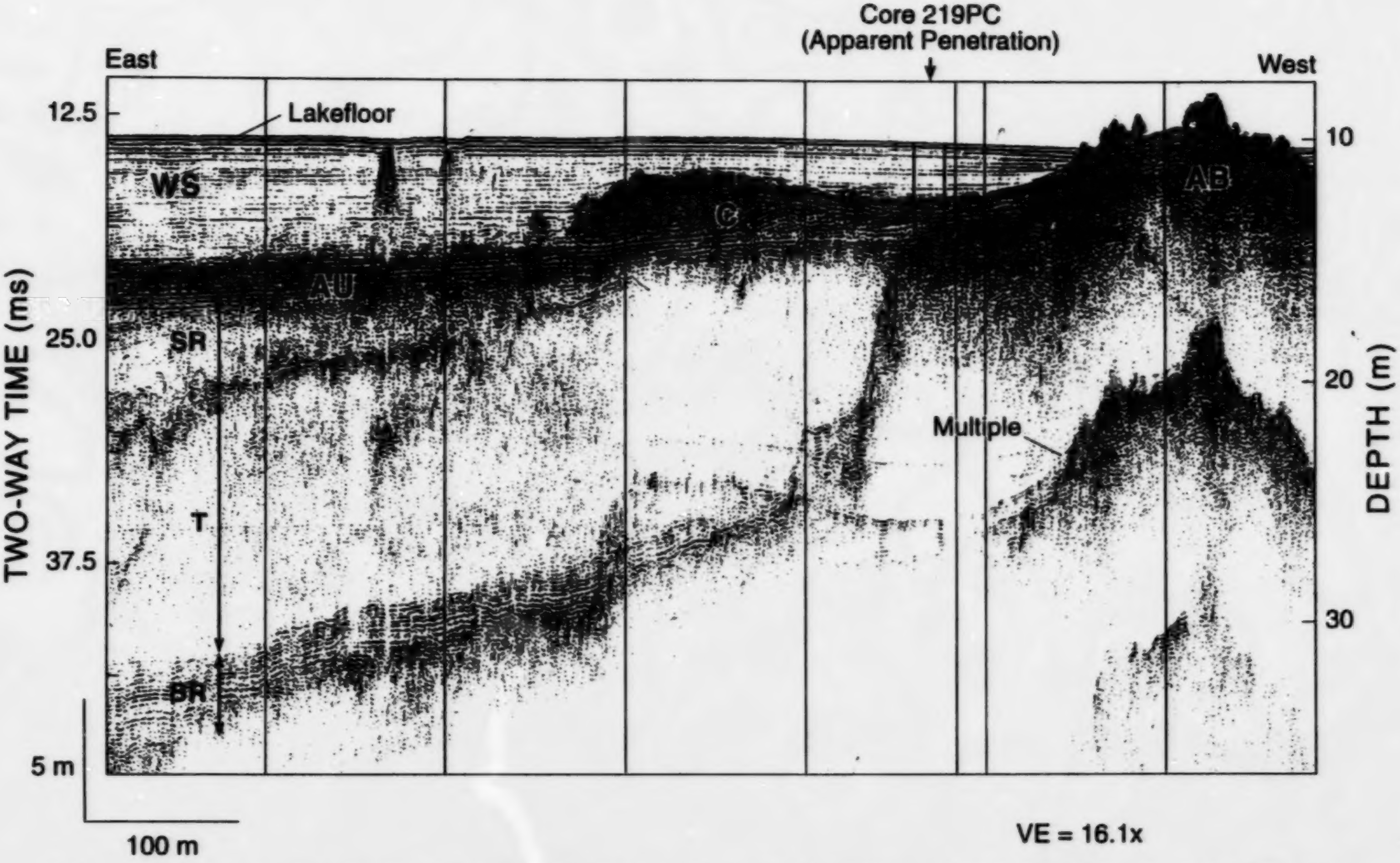
0-69 cm	**Clay mud;** soft, gray to dark gray (5Y4.5/1), noncalcareous. Surface dark grayish brown (10YR4/2) oxidized layer 0-0.5 cm, otherwise FeS stained and diffusely laminated to mottled and burrowed.
69-72 cm	**Muddy sand;** loose, dark gray (5Y4/1), noncalcareous.
72 cm	**Contact;** sharp, irregular.
72-115 cm	**Fine to medium sand;** dark grayish brown (2.5Y4/2). Slightly calcareous. Massive, slightly fining upward.
115-139 cm	**Sand;** as above with pods of mud and reddish, subangular pebbles to 1 cm of 'shield' affinity.

Core intervals equivalent to seismostratigraphic sequences:

0-139 cm	Winnipeg Sequence (Lake Winnipeg sediments including sand deposits below 72 cm).

Summary lithologic log for core 218PC correlated to seismostratigraphic sequences, southern Lake Winnipeg

Site 219

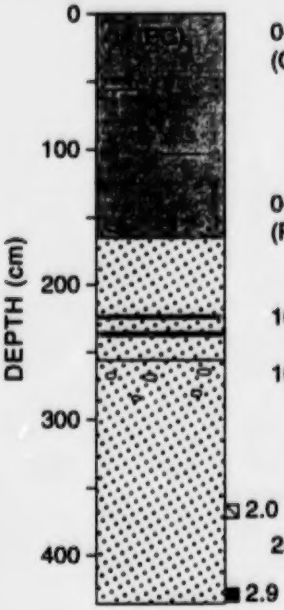


High resolution seismic reflection (Seistec) profile through core sites 218 and 219 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, C = Clinoforms, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence, SR = Segmented Reflective Interval, T = Transparent Interval, BR = Basal Reflective Interval. (Seistec record, Pearson Reef site survey, Day 242, 1996, 1608 UTC).

Site 219

Latitude:	50° 56.6' N	Gravity Core (GC):	10x119 cm
Longitude:	96° 41.0' W	GC Apparent Penetration:	180 cm
Lake Level, Depth:	217.8 m asl, 10.5 m	Piston (Solid) Core (PC):	10x439 cm
Date (Julian):	242/1846 (GC) and 242/1915 (PC)	PC Apparent Penetration:	396 cm

Lithology:



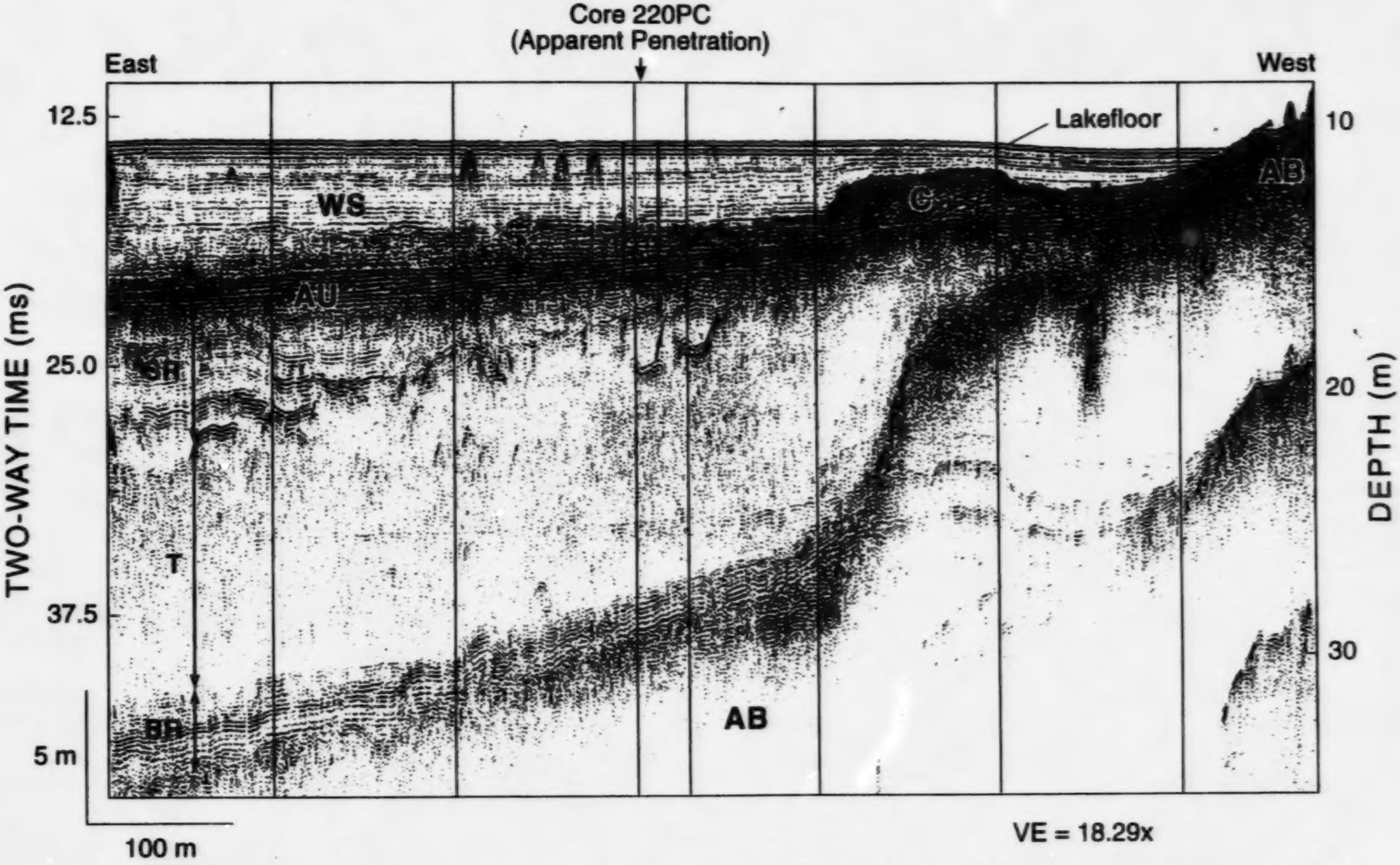
0-119 cm (GC)	**Clay mud;** very soft to soft, dark olive gray (5Y3/2) to olive gray (5Y4/2) near base, noncalcareous. Massive to 6 cm, then varying FeS content in cycles downcore. FeS horizontally streaked black units may be sharp-based and grade upward in each cycle. Heavily burrowed below 30 cm.
0-163 cm (PC)	**Clay mud;** very soft to soft, gray to olive gray (5Y5/1 to 5Y4/2), noncalcareous. Faintly, diffusely laminated with minor FeS black staining (speckles and streaks). Grades to unit below.
163-165 cm	**Muddy sand;** dark gray (5Y4/1), with black organic fragments.
165-258 cm	**Sand and mud;** mainly dark grayish brown (2.5Y4/2), noncalcareous fine sand, well rounded and massive, with poorly sorted fine to medium sand, granules and rare pebbles. Locally interbedded sand and mud with distinct 2 cm thick sandy mud beds between 221 and 233 cm.
258-439 cm	**Mud and sand;** interbedded coarse pebbly sand and silty clay mud, finer sand and fewer pebbles below 270 cm as proportion of mud increases toward base. Noncalcareous. Distinct beds of gray (5Y6/1), well rounded, quartz and lithic, fine to medium sand 312-319 cm, also similar bed but brown in colour 422-424 cm. Sand content in silty clay mud increases below 424 cm to well-rounded quartz sand in basal 2 cm with limestone pebble. At 372-377 cm, terrestrial beetle dated 1970±170 (CAMS 35494). At 436-439 cm, raspberry seeds dated 2940±80 (CAMS 35500).

Core intervals equivalent to seismostratigraphic sequences:

0-439 cm Winnipeg Sequence including basal clinoform reflectors (Lake Winnipeg sediments including sand deposits below 165 cm).

Summary lithologic log for cores 219GC and 219PC correlated to seismostratigraphic sequences, southern Lake Winnipeg

Site 220

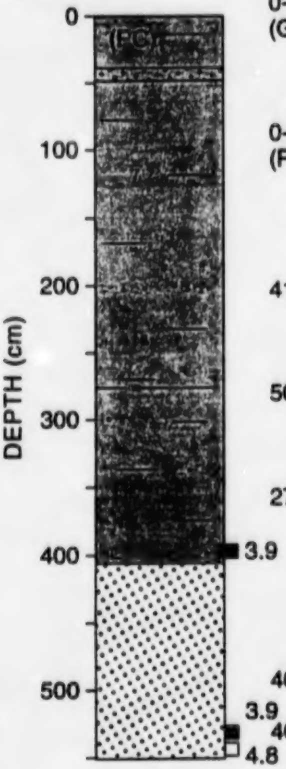


High resolution seismic reflection (Seistec) profile through core site 220 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, C = Clinoforms, AB = Acoustic Basement, AU = Agassiz Unconformity. Within the Agassiz Sequence, SR = Segmented Reflective Interval, T = Transparent Interval, BR = Basal Reflective Interval. (Seistec record, Pearson Reef site survey, Day 242, 1996, 1641 UTC).

Site 220

Latitude:	50° 56.8' N	Gravity Core (GC):	10x154 cm
Longitude:	96° 40.9' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.8 m asl, 10.5 m	Piston (Solid) Core (PC):	10x553 cm
Date (Julian):	242/2004 (GC) and 242/2024 (PC)	PC Apparent Penetration:	533 cm

Lithology:

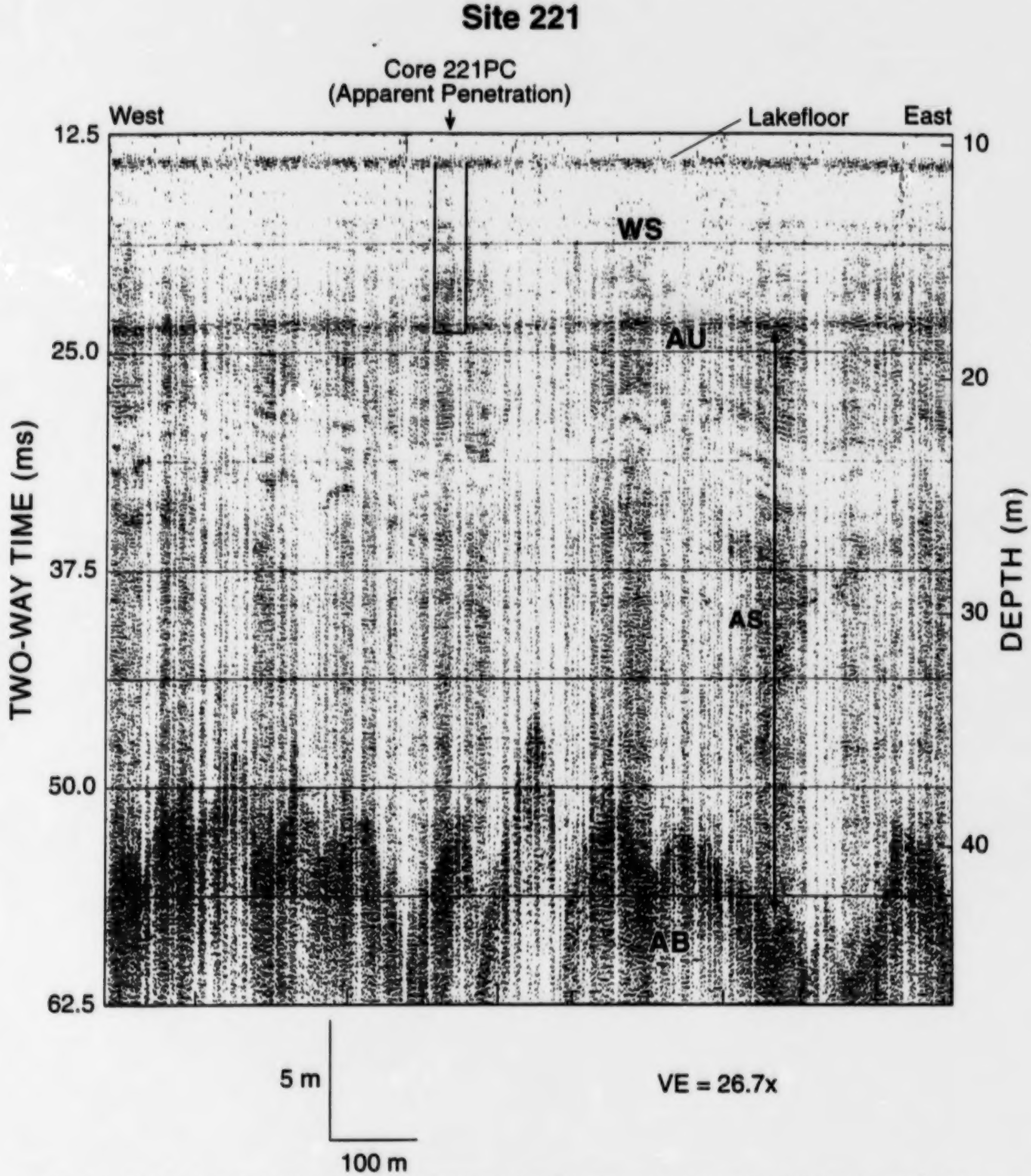


0-154 cm (GC)	**Clay mud;** very soft to soft, olive gray (5Y4/2) to dark olive gray (5Y3/2), noncalcareous. Black FeS streaking at 0-13, 20-43, 57-74, 102-105, 122-131 and 138-141 cm, becoming fainter downcore. Diffusely, fine-laminated to mottled with extensive burrowing.
0-41 cm (PC)	**Clay mud;** very soft, olive gray (5Y4/2) to dark olive gray (5Y3/2) to dark gray (5Y4/1). Noncalcareous; few slightly calcareous blebs near surface (ice-rafted?). High black FeS streaking, decreasing downcore. Diffusely fine laminated to mottled with extensive burrowing.
41-50 cm	**Fine to medium sand;** very dark gray (5Y3/1), organic, highly calcareous (1 cm) over dark grayish brown (2.5Y4/2) well-rounded quartz sand.
50-276 cm	**Clay mud;** soft, olive gray (5Y4/2) to gray (5Y5/1). Noncalcareous. Local FeS concentrations. Massive to diffusely laminated, mottled and burrowed. Thin 8mm calcareous fine sand bed at 201 cm.
276-407 cm	**Silty clay mud;** soft to firm, olive gray (5Y4.4/2). Noncalcareous. Diffusely laminated and black FeS streaked. Sandy balls and blebs (cm-scale) scattered throughout, in places aligned in crude strata. Wood and other organic fragments below 390 cm. At 395-400 cm, *Polygonum amphibium* L. seed dated 3870±140 (CAMS 46193).
407 cm	**Contact;** distinct, conformable.
407-553 cm	**Sand;** fine, brown, calcareous, containing well-rounded quartz grains. Mainly massive, possibly flowed in core. Granules and some organics with silt 460-500 cm. Two beds of graded fine pebble gravel 490-496 cm. Dark gray (5Y4/1) fine-medium well-rounded sand below 500 cm, becoming gritty down-core with increasing organic content below 530 cm. Crystalline pebble 540 cm, articulated 6-cm pelecypod 545 cm, silty fine-coarse sand with abundant organics below 550 cm. At 535-540 cm, goosefoot (*Chenopodium*) seeds dated 3920±70 (CAMS 35495); at 542-547 cm, pelecypod shell dated 4760±70 (CAMS 32193). Lower 20 cm could be sucked in sediment.

Core intervals equivalent to seismostratigraphic sequences:

0-553 cm	Winnipeg Sequence (Lake Winnipeg sediments including sand deposits below 407 cm).

Summary lithologic log for cores 220GC and 220PC correlated to seismostratigraphic sequences, southern Lake Winnipeg



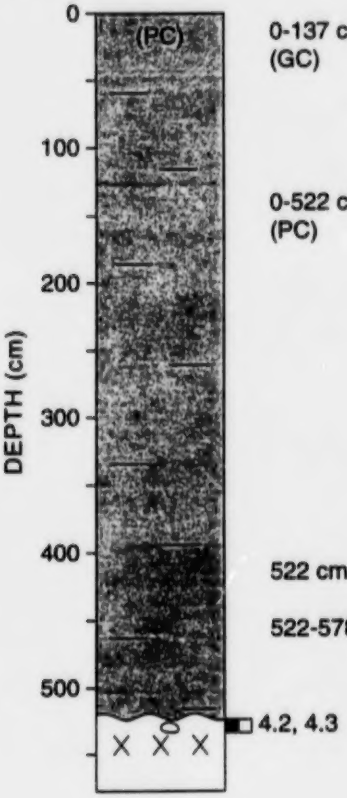
High resolution seismic reflection (Seistec) profile through core site 221 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AB = Acoustic Basement, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line SB14, Day 226, 1996, 1829 UTC).

Site 221

Latitude: 50° 56.1' N
Longitude: 96° 37.0' W
Lake Level, Depth: 217.9 m asl, 10.4 m
Date (Julian): 243/1538 (GC) and 247/1705 (PC)

Gravity Core (GC): 10x137 cm
GC Apparent Penetration: 200 cm
Piston (Solid) Core (PC): 10x578 cm
PC Apparent Penetration: 701 cm

Lithology:



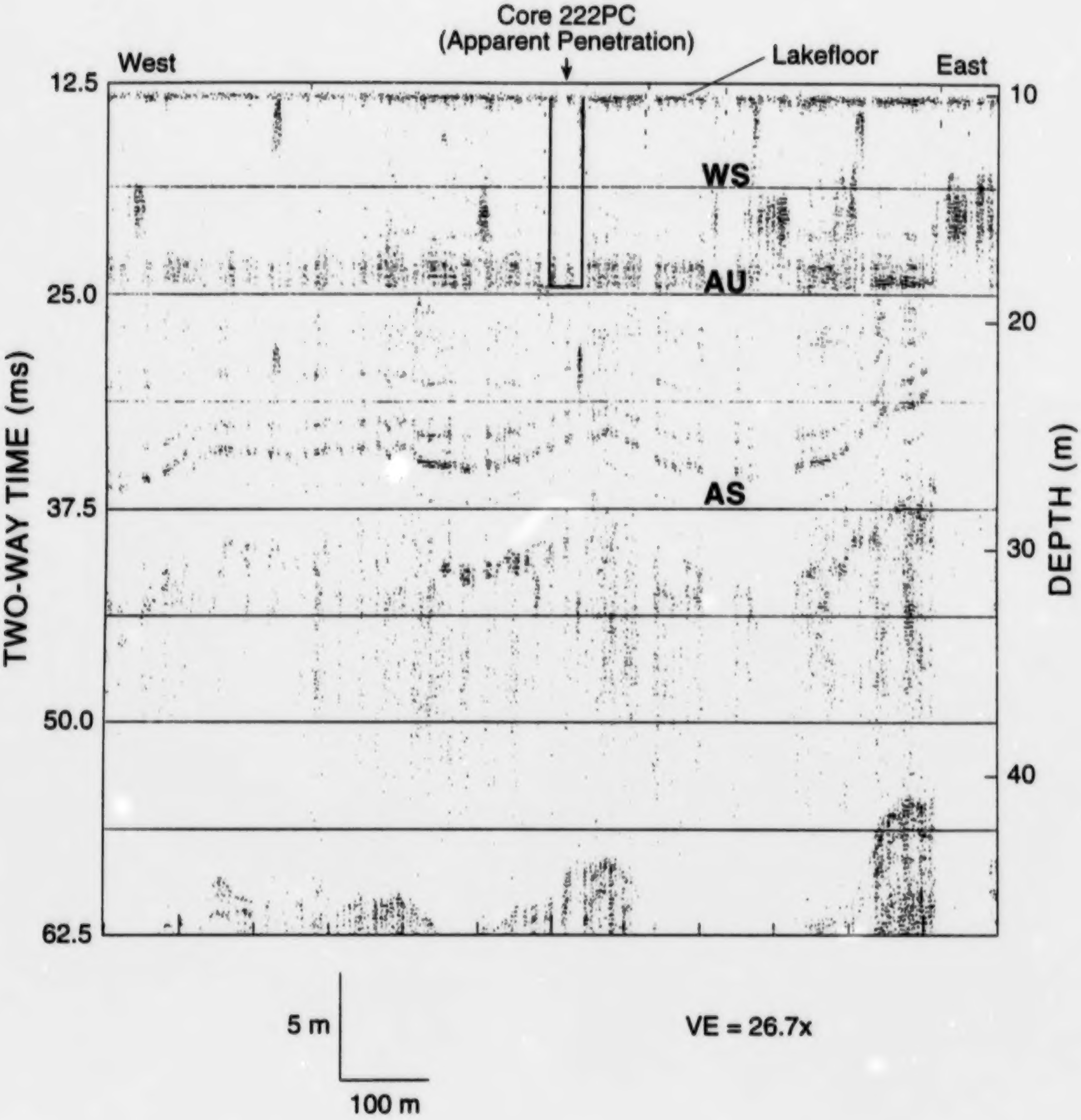
0-137 cm (GC)	**Clay mud;** very soft to soft, gray (5Y5/1), noncalcareous. Surface dark brown (10YR3/3) to olive brown (2.5Y4/4) oxidized layer, 0-0.5 cm. Black-streaked (5Y2.5/1) and diffusely, irregularly laminated and mottled (bioturbated) throughout; black streaking decreases downcore.
0-522 cm (PC)	**Clay mud to silty clay mud;** soft, gray (5Y5/1), noncalcareous. Surface dark brown (10YR3/3) to olive brown (2.5Y4/4) oxidized layer, 0-0.5 cm. Black (5Y2.5/1) streaked, diffusely mottled (bioturbated) and incipiently banded at irregular intervals throughout; black decreases downcore. H_2S odour generated by HCl addition. Distinct gray zone (absence of black streaking) 242-254 cm. Fewer black specks and less H_2S odour below 360 cm.
522 cm	**Contact;** sharp, erosional.
522-578 cm	**Clay;** stiff, crumbly, gray (5Y5/1), highly calcareous. Transition to less crumbly, smooth, dark gray (5Y4/1) clay 555-562 cm. Bivalve, articulated in growth position 526-527 cm. At 523-528 cm, *Scirpus* sp. seed dated 4190±100 (CAMS 38680); at 526-527 cm, *Sphaerium striatinum* bivalve dated 4320±50 (CAMS 35616). Interpreted as age of flora and fauna living on surface of stiff clay before onset of mud sedimentation, 0-522 cm.

Core intervals equivalent to seismostratigraphic sequences:

0-522 cm	Winnipeg Sequence (Lake Winnipeg sediments).
522-578 cm	Agassiz Sequence (Lake Agassiz sediments).

Summary lithologic log for cores 221GC and 221PC correlated to seismostratigraphic sequences, southern Lake Winnipeg

Site 222

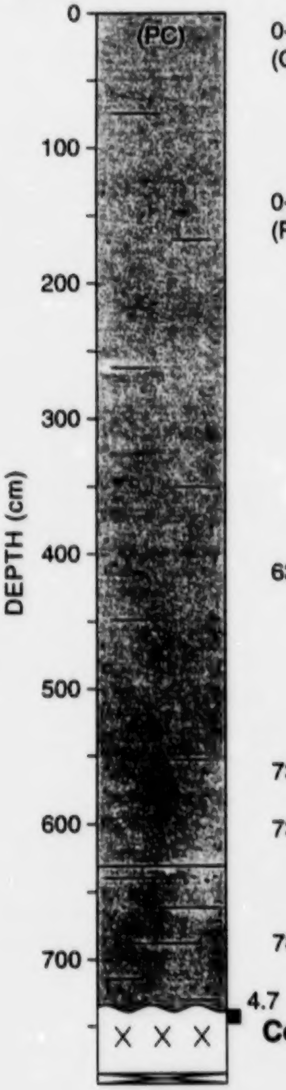


High resolution seismic reflection (Seistec) profile through core site 222 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. WS = Winnipeg Sequence, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line SB14, Day 226, 1996, 1710 UTC).

Site 222

Latitude:	50° 56.1' N	Gravity Core (GC):	10x146 cm
Longitude:	96° 44.2' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.9 m asl, 10.4 m	Piston (Solid) Core (PC):	10x786 cm
Date (Julian):	243/1623 (GC) and 247/1601 (PC)	PC Apparent Penetration:	838 cm

Lithology:

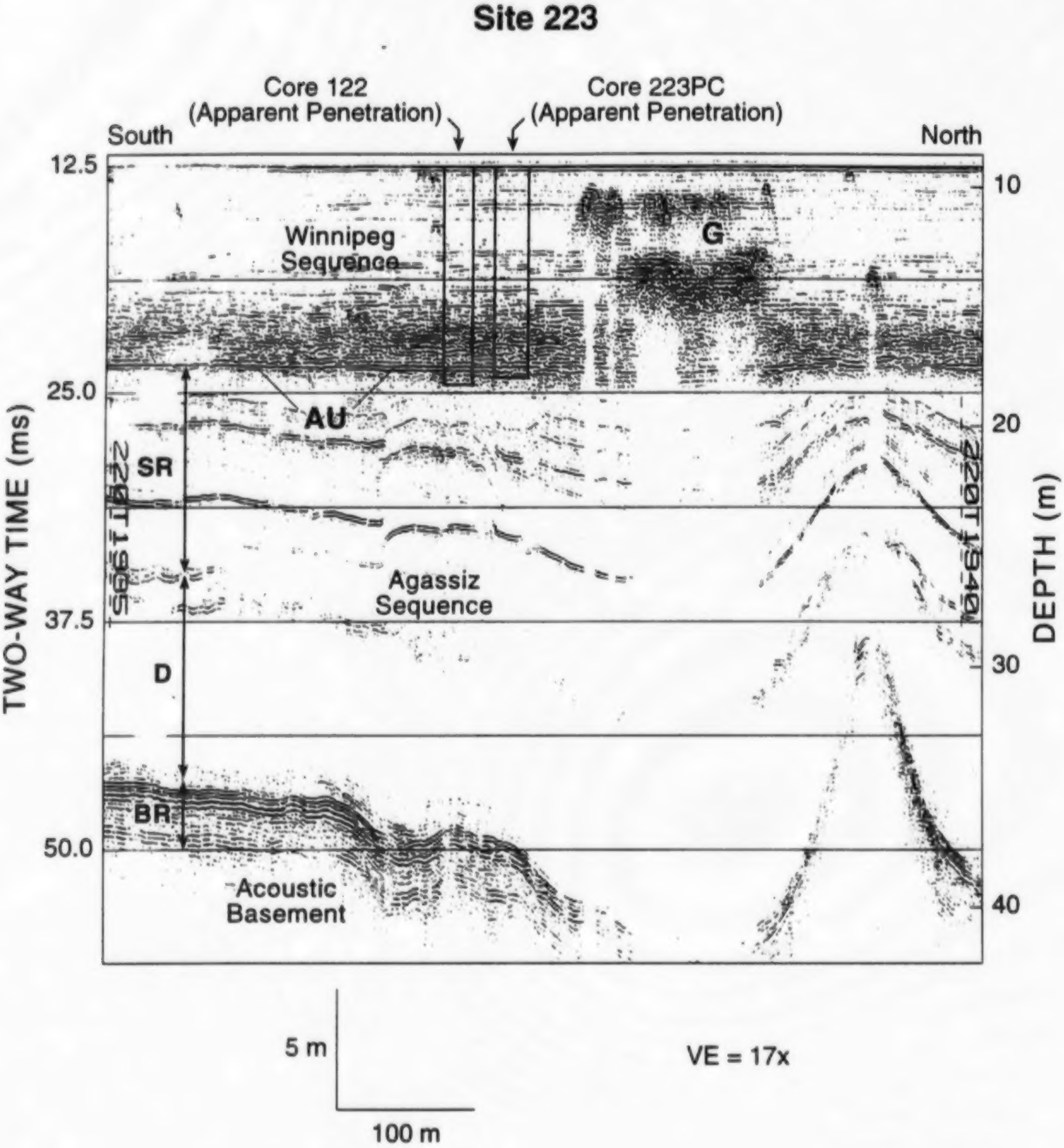


0-146 cm (GC)	**Clay mud;** very soft to soft, olive gray (5Y4/2), noncalcareous. Surface dark grayish brown (10YR4/2) oxidized layer 0-0.5 cm. Diffuse mottling and burrows with intermittent horizontal black FeS streaking; rare black streaking below 77 cm. Organic fragments at 115 cm.
0-632 cm (PC)	**Clay mud;** soft, olive gray (5Y4/2) then gray (5Y4/1) to dark gray (5Y4.5/1) below 35 cm. Noncalcareous throughout. Diffuse mottling, burrowing and incipient lamination. Black FeS streaking common above 49 cm, sparse below, and cyclic at 10-20 cm intervals between 240 and 490 cm. Flame structure 574-598 cm.
632-735 cm	**Silty clay mud;** soft to firm, gray to dark gray (5Y4.8/1), noncalcareous with grit and small pebbles. Diffusely fine-laminated with minor silt lenses, occasional organic fragments and shells. Vent structure with laminated fill 690-695 cm. Contorted zones 674-678, 680-695 cm.
735 cm	**Contact;** sharp, erosional.
735-786 cm	**Silty clay;** stiff, crumbly olive gray (5Y4/2) to dark gray (5Y4.5/1), calcareous. At 735-740 cm *Scirpus* sp. seed dated 4710±50 (CAMS 46188).
786-792 cm	Recored mud.

Core intervals equivalent to seismostratigraphic sequences:

0-735 cm	Winnipeg Sequence (Lake Winnipeg sediments).
735-786 cm	Agassiz Sequence (*in situ* or reworked Lake Agassiz sediments).

Summary lithologic log for cores 222GC and 222PC correlated to seismostratigraphic sequences, southern Lake Winnipeg



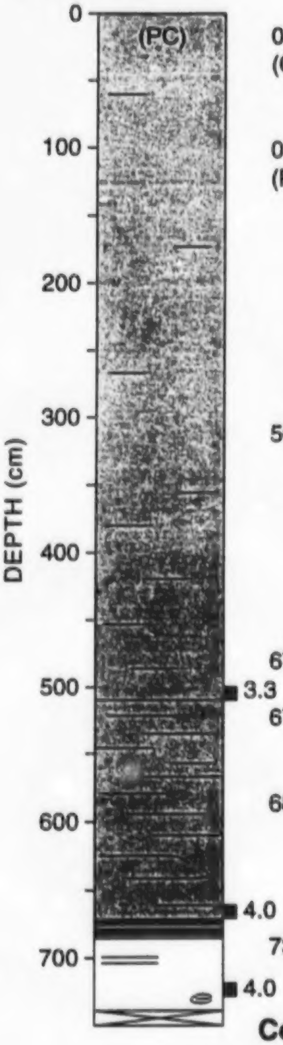
Site 223

High resolution seismic reflection (Seistec) profile through core site 223 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. G = gas masking, AU = Agassiz Unconformity. Within the Agassiz Sequence, SR = Segmented Reflective Interval, T = Transparent Interval, BR = Basal Reflective Interval. (Seistec record, line SB3, Day 220, 1994, 1935 UTC).

Site 223

Latitude:	50° 39.4' N	Gravity Core (GC):	10x155 cm
Longitude:	96° 48.3' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.6 m asl, 9.75 m	Piston (Solid) Core (PC):	10x739 cm
Date (Julian):	243/1812 (GC) and 243/1831 (PC)	PC Apparent Penetration:	838 cm

Lithology:



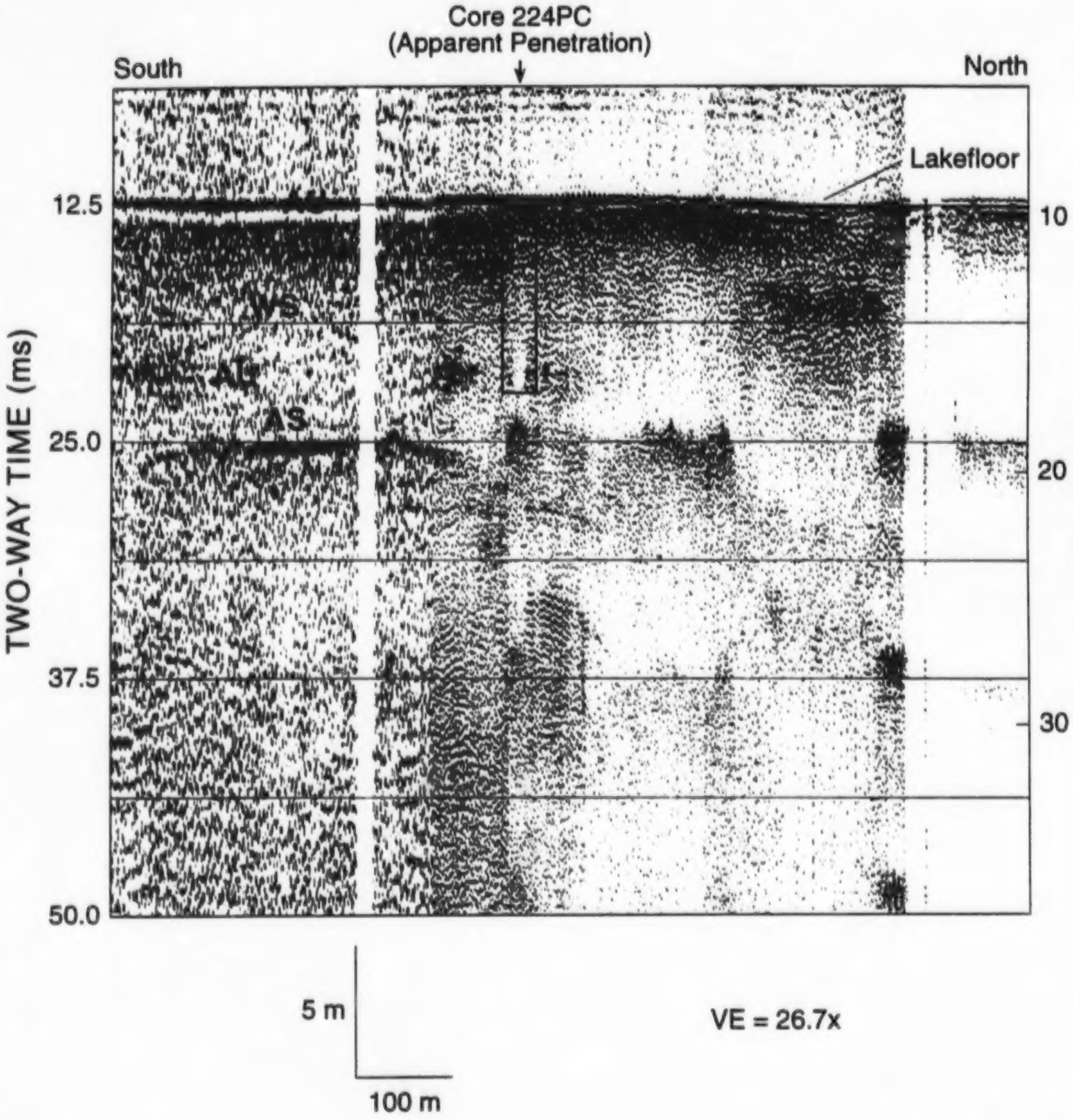
0-155 cm (GC)	**Clay mud;** very soft to soft, olive gray (5Y4/2), noncalcareous. Diffusely mottled with finely disseminated organics throughout. Black FeS streaking below 25 cm. Hint of lamination below 110 cm.
0-509 cm (PC)	**Clay mud;** soft, gray to dark gray (5Y4.5/1), noncalcareous. Surface olive brown (2.5Y4/4) oxidized layer 0-0.5 cm. Intermittently and diffusely laminated and mottled (burrowed); incipient lamination below 365 cm. Black FeS streaking common 0-20 cm, less obvious below. At 504-509 cm, shell and plant fragments in tilted layer. *Scirpus* seed dated 3280±60 (CAMS 34550).
509-677.5 cm	**Silty clay mud;** soft to firm, gray to dark gray (5Y4.5/1). Weakly to moderately calcareous. Finely laminated (mm-scale) in places with scattered calcareous, lenticular silt laminae; also two thicker layers (1 cm) with black organic fragments. Contorted zones common, e.g. recumbently folded laminations. At 661-666 cm, *Scirpus* seed dated 4000±60 (CAMS 34551).
677.5 cm	**Contact;** sharp.
677.5-687 cm	**Silty peat;** firm, black (5Y2.5/2). Very weakly calcareous. Vertical black zones (root casts?). Organics concentrated in basal 2 cm.
687-739 cm	**Organic silty clay;** firm, crumbly, dark olive gray (5Y3/2). Weakly to highly calcareous. Organic-rich layer 700-704 cm, organics in ball form 717-724 cm. At 721-726 cm, *Scirpus* sp. seed dated 4030±50 (CAMS 46186).
739-746 cm	Sucked-in soft mud (recored material).

Core intervals equivalent to seismostratigraphic sequences:

0-687 cm	Winnipeg Sequence (Lake Winnipeg sediments).
687-739 cm	probably Agassiz Sequence because of firm consistency (reworked Lake Agassiz sediments?).

Summary lithologic log for cores 223GC and 223PC correlated to seismostratigraphic sequences, southern Lake Winnipeg

Site 224

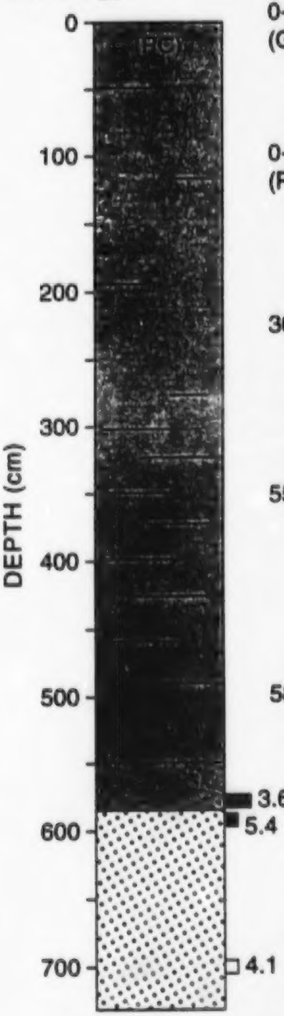


High resolution seismic reflection (Seistec) profile through core site 224 in South Basin, Lake Winnipeg, showing seismostratigraphic sequences. VE = Vertical Exaggeration, vertical scale bar assumes a sound velocity of 1500 m/s. G = gas masking, WS = Winnipeg Sequence, AU = Agassiz Unconformity, AS = Agassiz Sequence (undifferentiated). (Seistec record, line SB1, Day 216, 1994, 1930 UTC).

Site 224

Latitude:	50° 33.0' N	Gravity Core (GC):	10x143 cm
Longitude:	96° 47.2' W	GC Apparent Penetration:	200 cm
Lake Level, Depth:	217.9 m asl, 8.5 m	Piston (Solid) Core (PC):	10x731 cm
Date (Julian):	247/1942 (GC) and 247/1959 (PC)	PC Apparent Penetration:	762 cm

Lithology:



0-143 cm (GC)	**Clay mud;** very soft to soft, gray (5Y4,5/1), noncalcareous. Surface brown (10Y4/3) oxidized layer 0-0.5 cm. Massive 0-24 cm, then occasional zones of faint lamination and diffuse mottling. Black FeS specks common but decrease downcore.
0-302 cm (PC)	**Clay mud to silty clay mud;** soft, gray to dark gray (5Y4.5/1), noncalcareous. Surface brown (10Y4/3) oxidized layer. Massive to intermittent, alternating zones of diffuse lamination and burrowing. Some black FeS speckling and streaking in upper 5 cm, minor below.
302-550 cm	**Silt-clay mud;** soft, gray to dark gray (5Y4.5/1). Faintly, diffusely, fine to thickly laminated, contorted in places. Thin (mm-scale) silt lenses and laminae, more frequent downcore. Calcareous below 400 cm. Occasional black FeS specks and streaks. Grades to unit below.
550-583 cm	**Mud and sand;** soft, gray to dark gray (5Y4.5/1). Fine sand layers, cm-scale, in silt-clay mud, calcareous. Organics abundant - small gastropod shells, wood fragments, plant detritus and black FeS lenses. Grades to unit below. At 577-582, *Helianthus* seed dated 3550±70 (CAMS 35496), and *Scirpus* seed dated 3570±120 (CAMS 35501)
583-731 cm	**Sand;** dark gray (5Y4/1), fine to medium sand, coarse and poorly sorted in places. Mainly angular to well-rounded quartz grains, some limestone fragments. Highly calcareous. Massive with inclusions of mud clasts, 5-13 cm wide containing organic fragments and a wood piece. Unit looks resedimented. Shells and shell fragments scattered throughout, more numerous below 700 cm. At 584-589 cm, an abraded (transported) *Scirpus* sp. seed dated 5350±50 (CAMS 46192). At 705-710 cm, one bivalve half-shell dated 4090±60 (CAMS 35615). Lower 30 cm could be sucked-in sediment.

Core intervals equivalent to seismostratigraphic sequences:

0-731 cm Winnipeg Sequence (Lake Winnipeg sediments).

Summary lithologic log for cores 224GC and 224PC correlated to seismostratigraphic sequences, southern Lake Winnipeg

Appendix 10.5

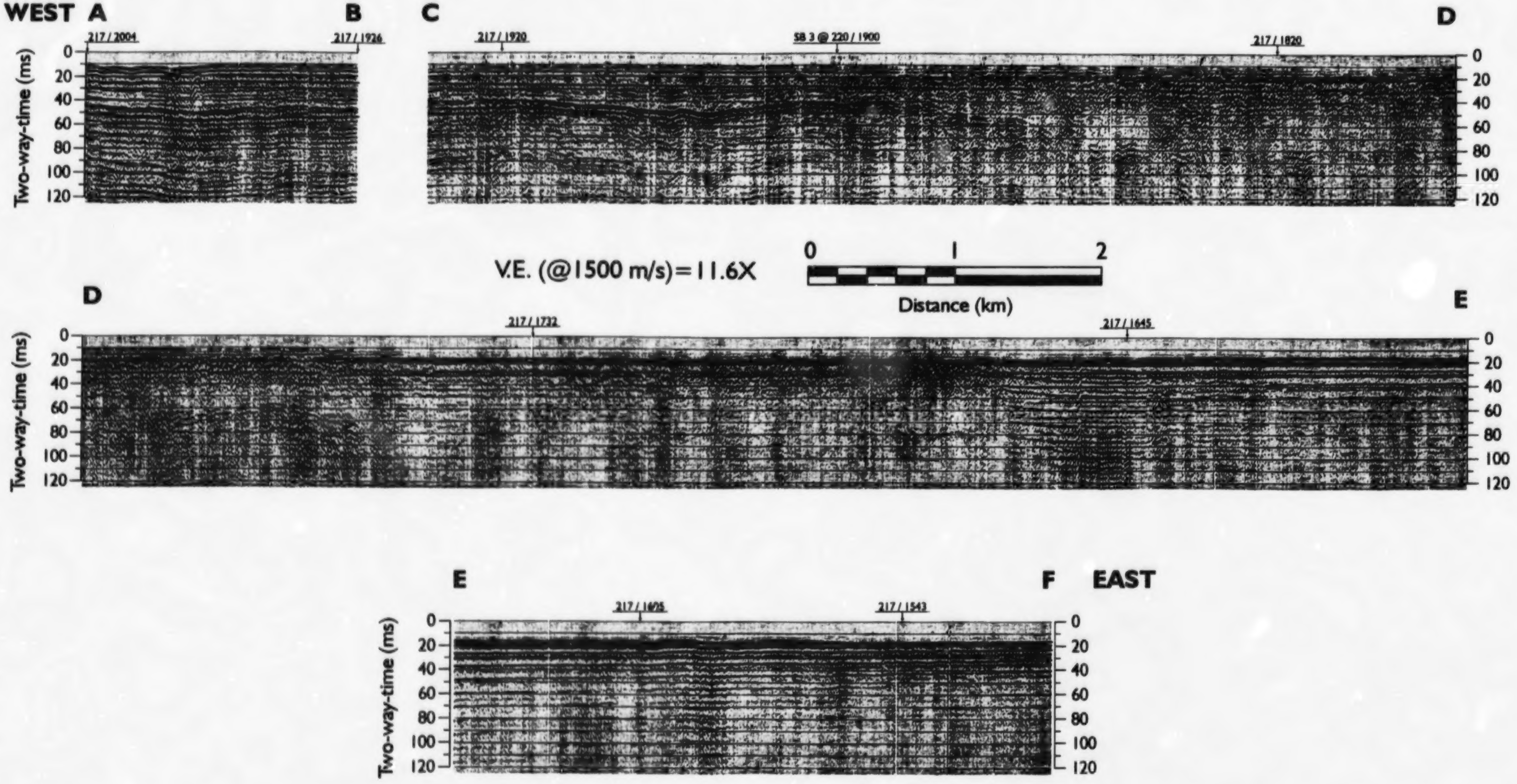
Sleevegun seismic profiles

S.E. Pullan[1], R.A. Burns[1] and B.J. Todd[2]

1. Geological Survey of Canada, Ottawa
2. Geological Survey of Canada (Atlantic)

LAKE WINNIPEG PROJECT SEISMIC PROFILES

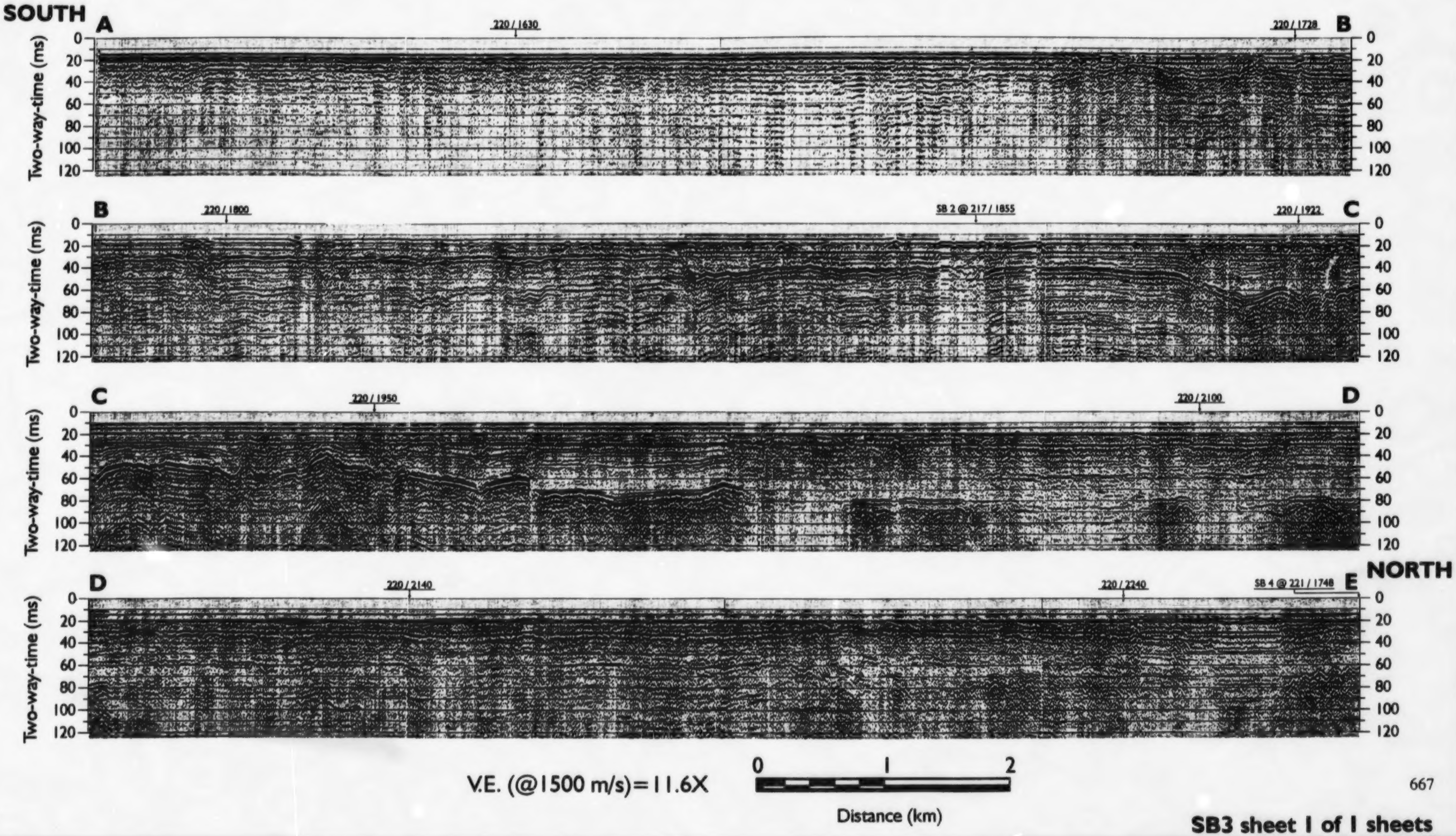
SOUTH BASIN LINE 2



SB2 sheet 1 of 1 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES

SOUTH BASIN LINE 3

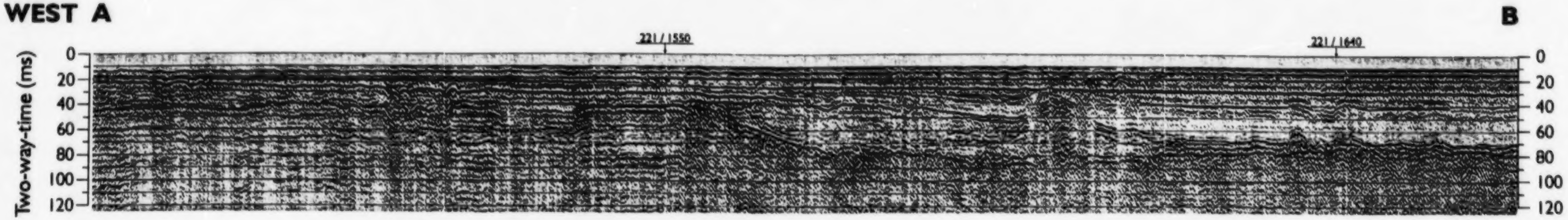


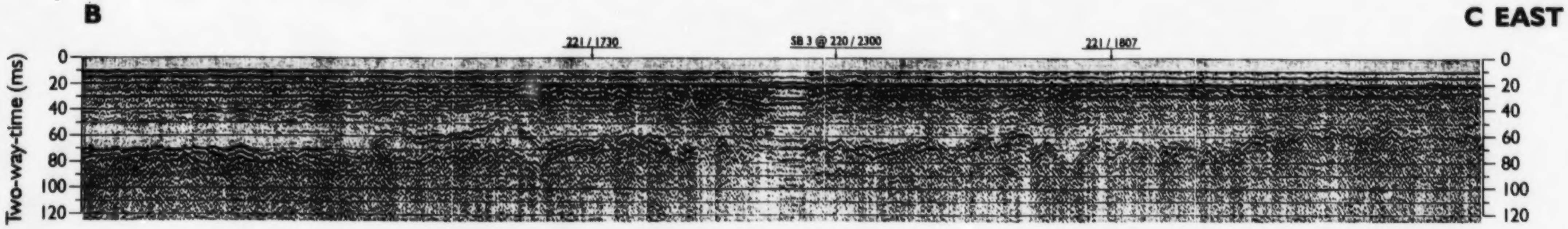
SB3 sheet 1 of 1 sheets

Natural Resources Canada Ressources naturelles Canada

LAKE WINNIPEG PROJECT SEISMIC PROFILES

SOUTH BASIN LINE 4





V.E. (@1500 m/s) = 11.6X

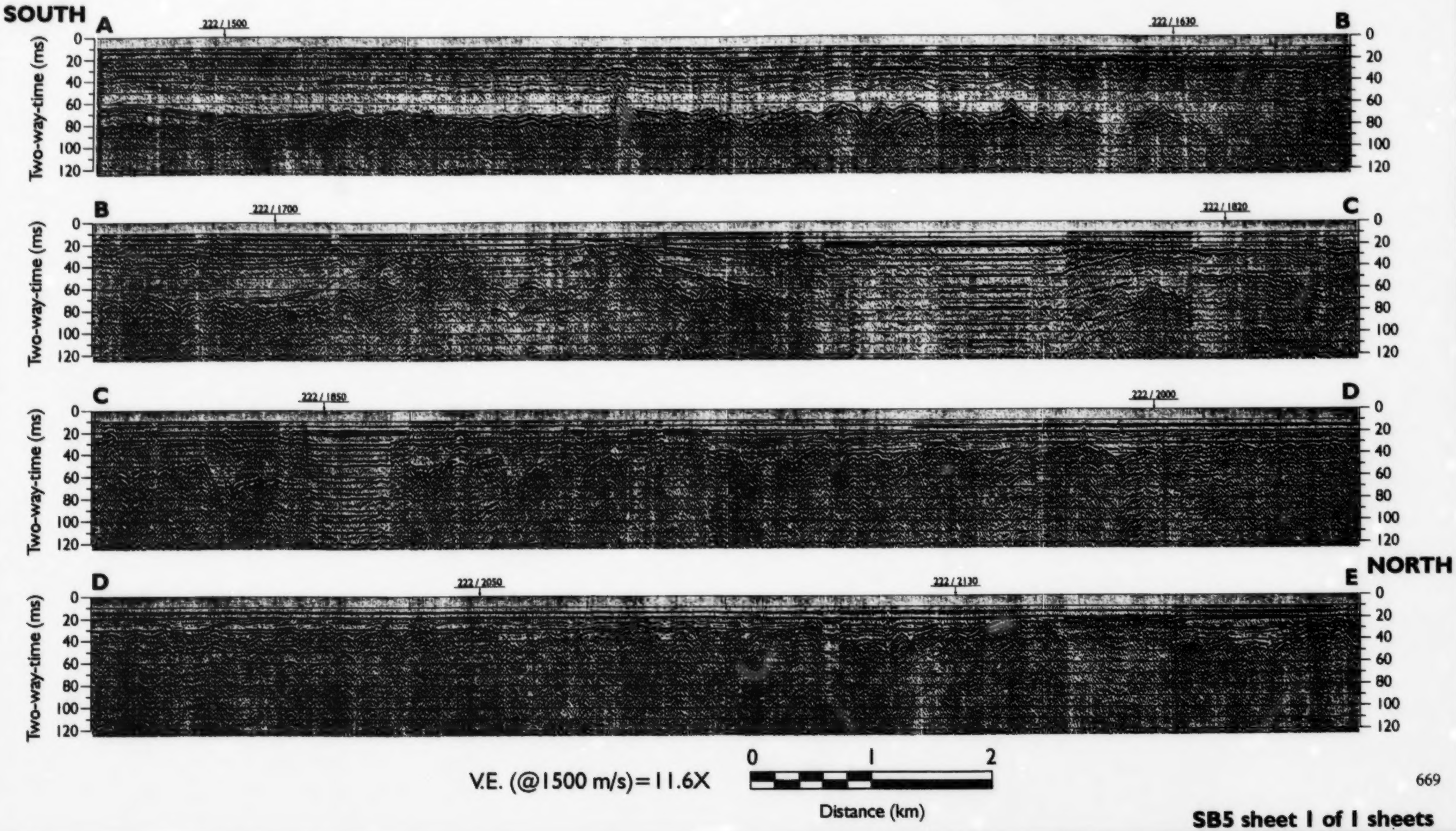
0 1 2

Distance (km)

SB4 sheet 1 of 1 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES

SOUTH BASIN LINE 5

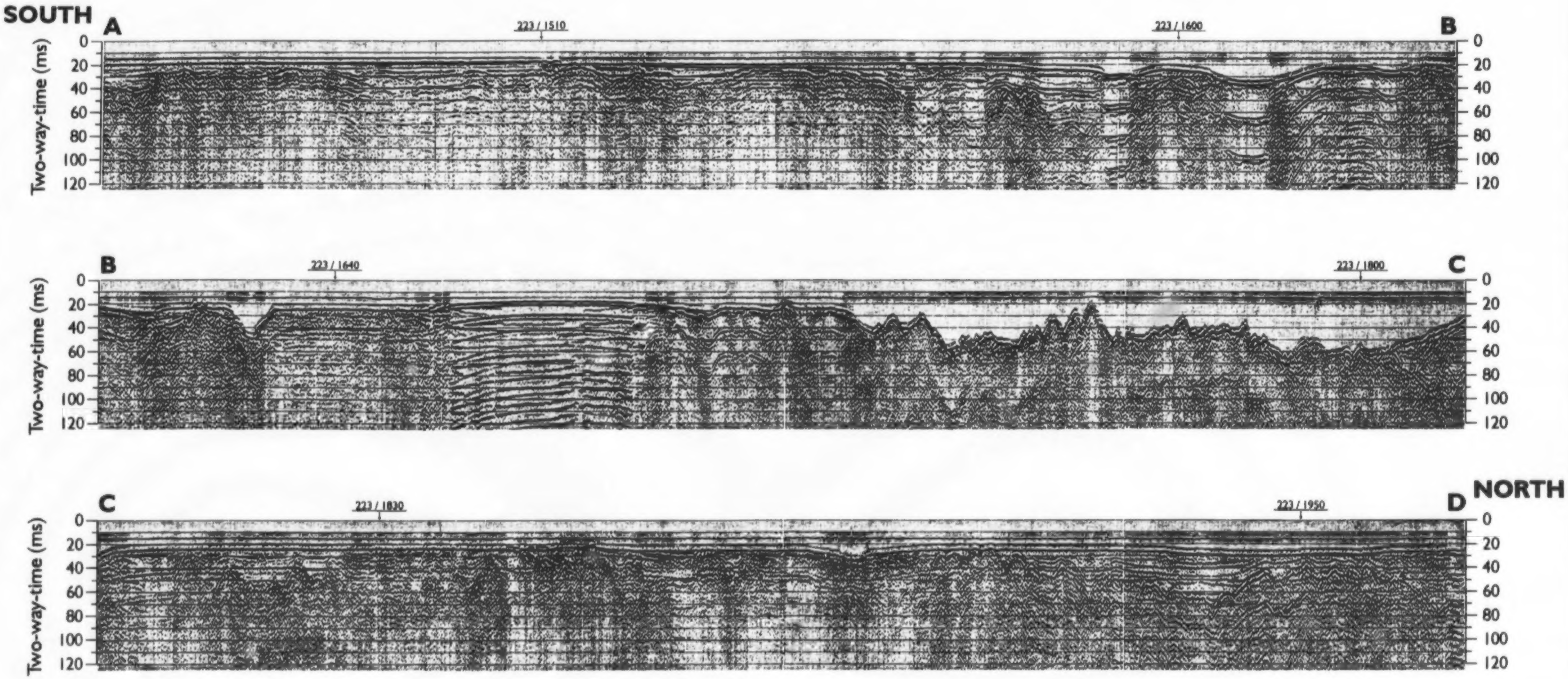


669

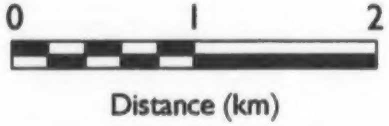
SB5 sheet 1 of 1 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES

SOUTH BASIN LINE 6



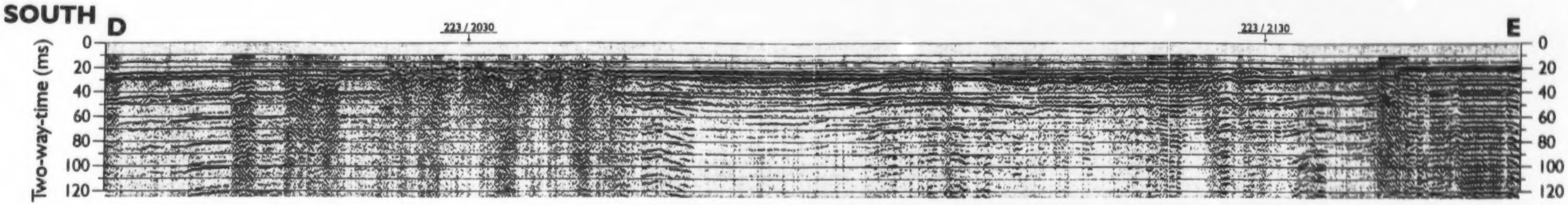
V.E. (@1500 m/s)=11.6X


0
1
2
Distance (km)

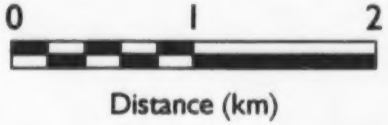
SB6 sheet 1 of 2 sheets

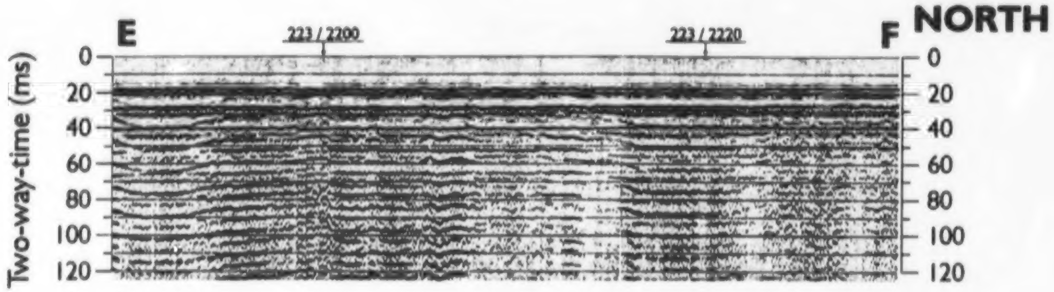
LAKE WINNIPEG PROJECT SEISMIC PROFILES

SOUTH BASIN LINE 6



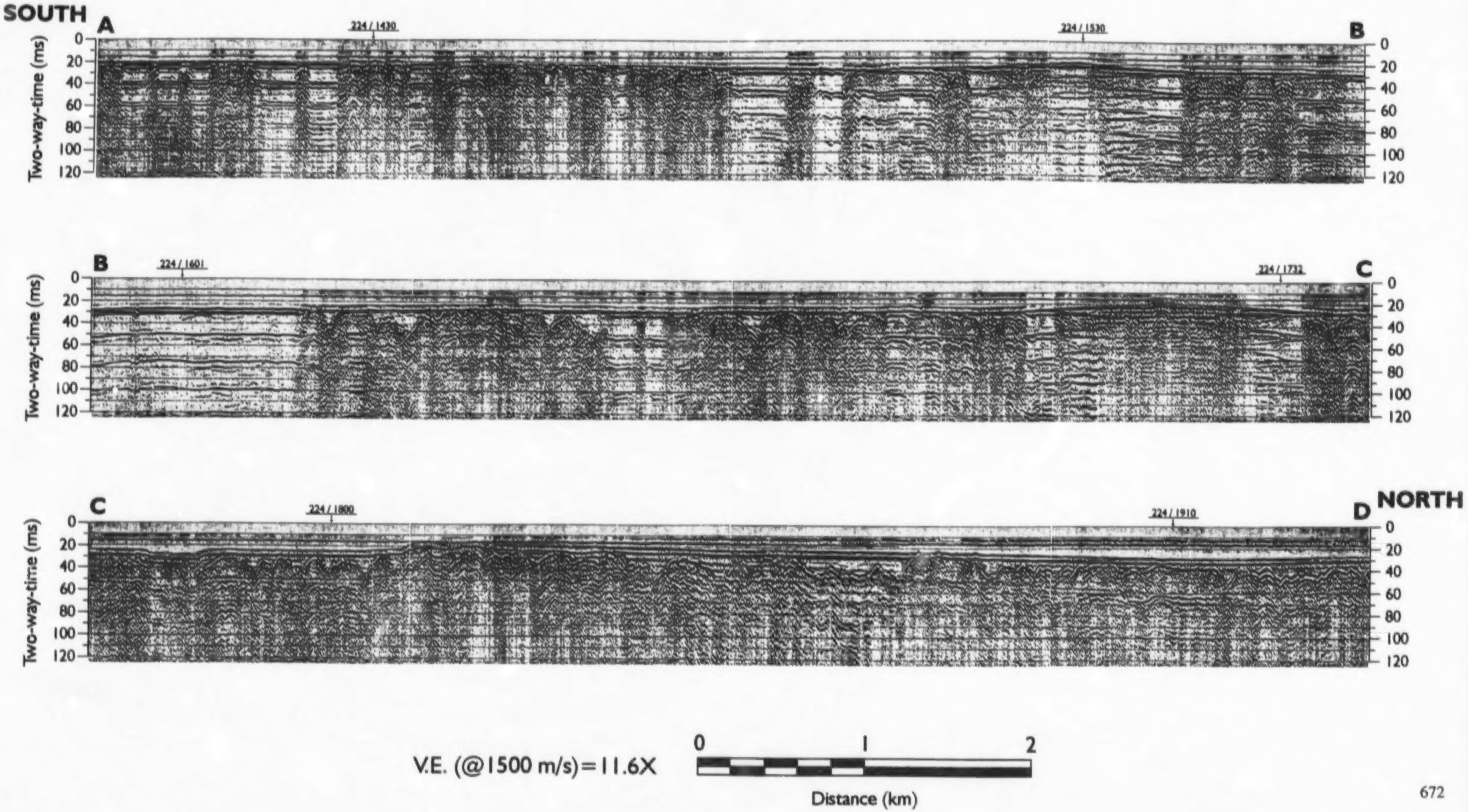
V.E. (@1500 m/s)=11.6X





LAKE WINNIPEG PROJECT SEISMIC PROFILES

SOUTH BASIN LINE 7

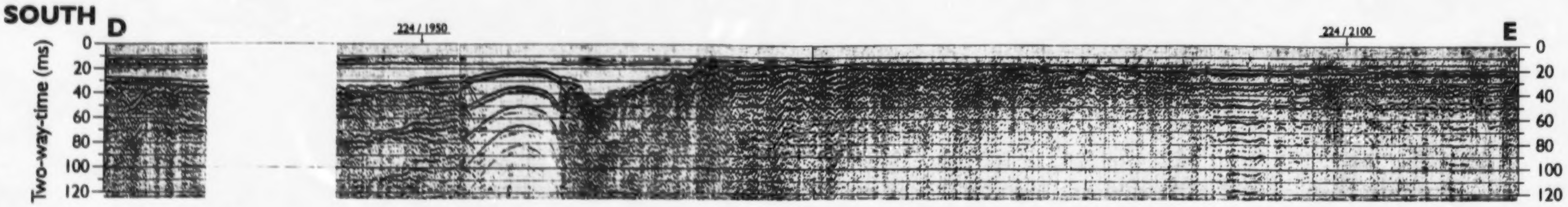


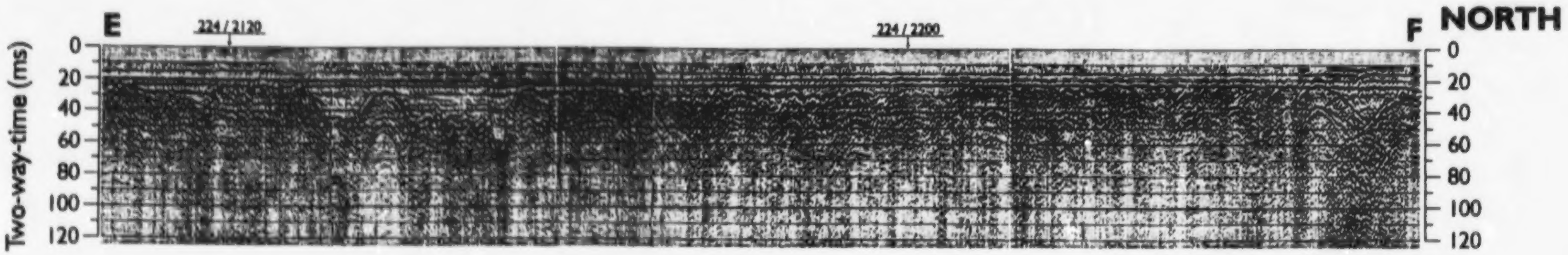
672

SB7 sheet 1 of 2 sheets

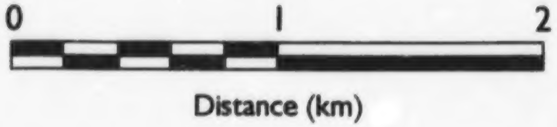
LAKE WINNIPEG PROJECT SEISMIC PROFILES

SOUTH BASIN LINE 7





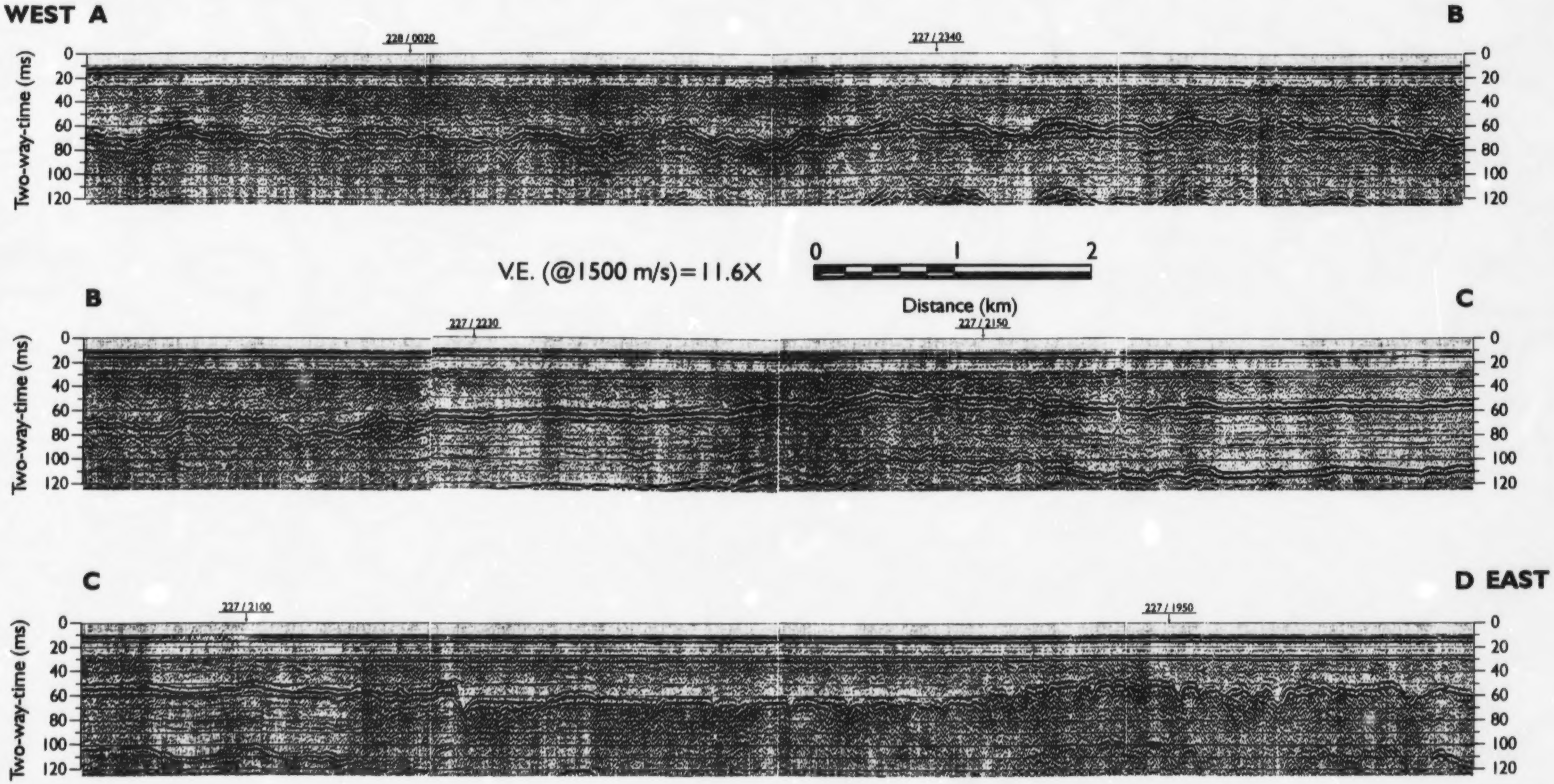
V.E. (@1500 m/s)=11.6X


0
1
2
Distance (km)

Natural Resources Canada Ressources naturelles Canada

LAKE WINNIPEG PROJECT SEISMIC PROFILES

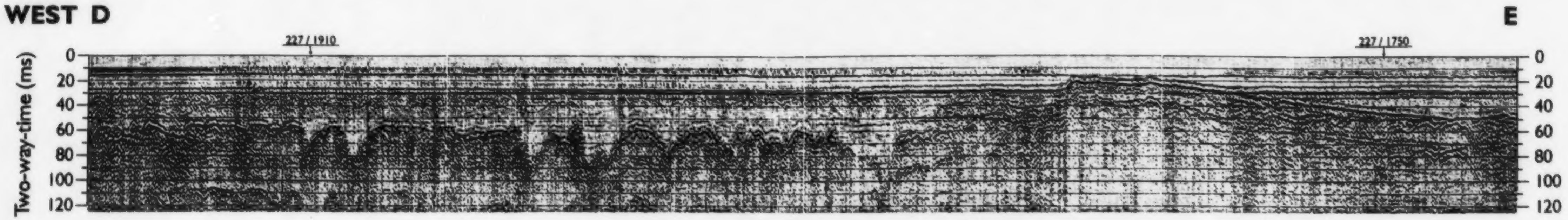
NORTH BASIN LINE 8



NB8 sheet 1 of 2 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES

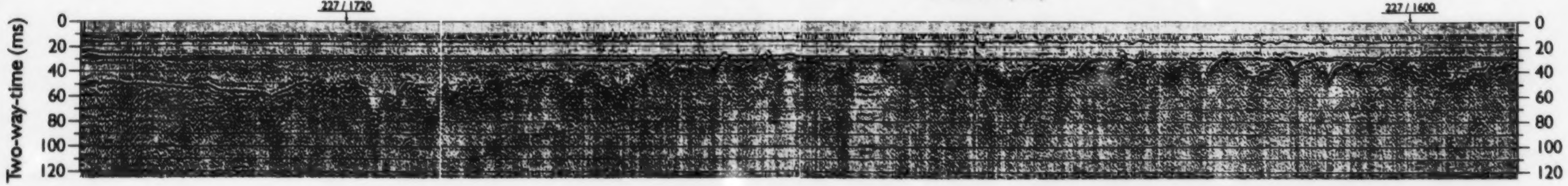
NORTH BASIN LINE 8

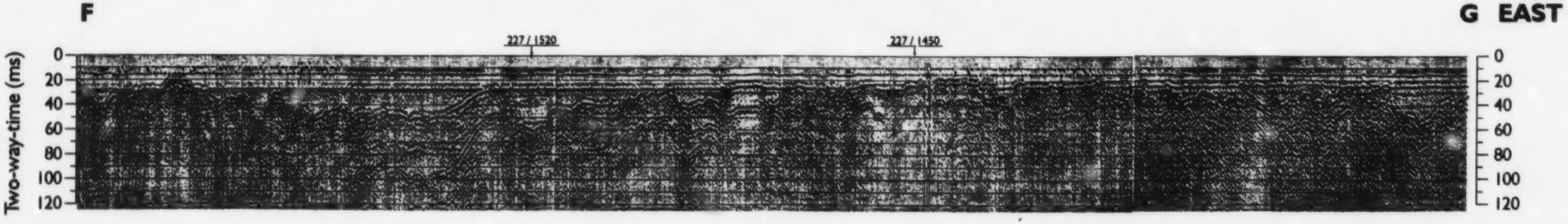


V.E. (@1500 m/s)=11.6X

0 1 2

Distance (km)





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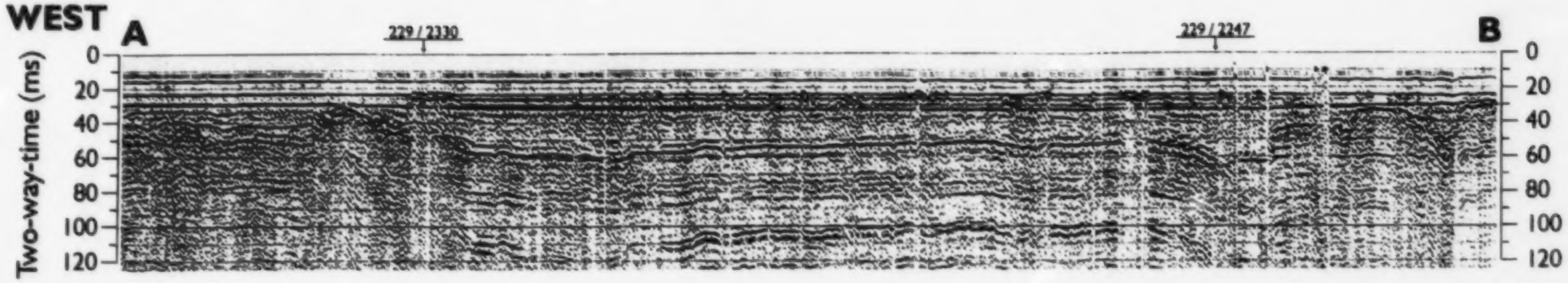
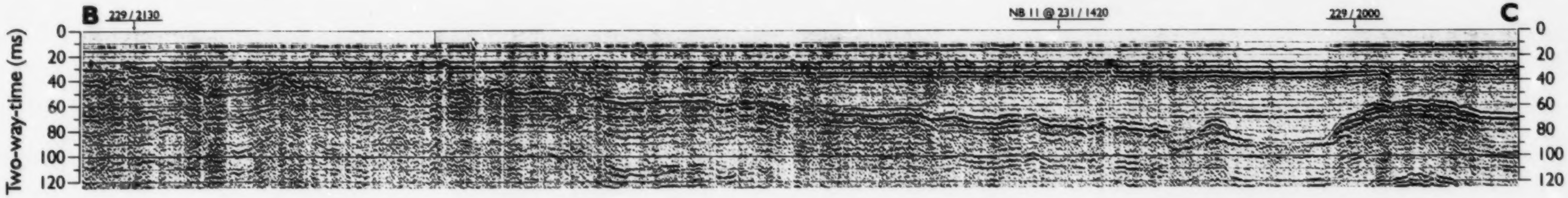
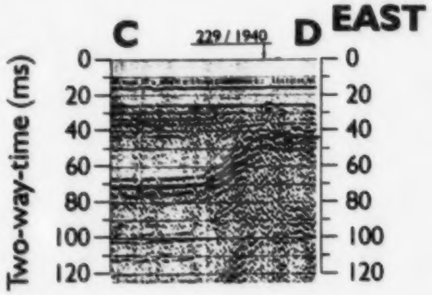
LAKE WINNIPEG PROJECT SEISMIC PROFILES

NORTH BASIN LINE 9



DATA GAP





DATA GAP

V.E. (@1500 m/s)=11.6X

0 1 2

Distance (km)

NB9 sheet 1 of 1 sheets

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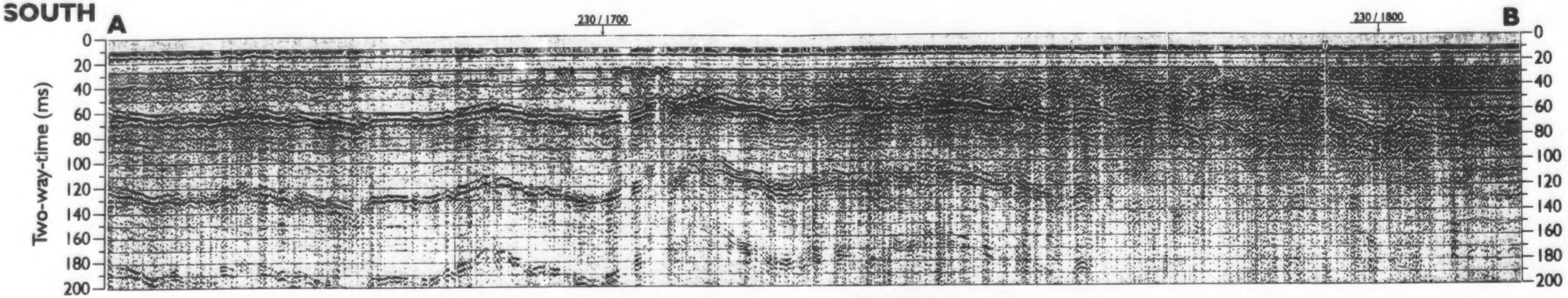
LAKE WINNIPEG PROJECT SEISMIC PROFILES

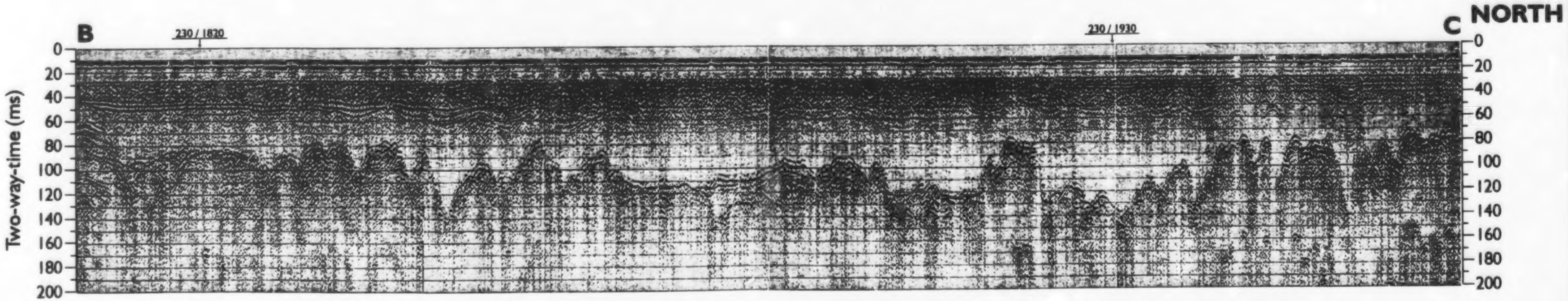
NORTH BASIN LINE 10



V.E. (@1500 m/s)=11.6X

0 1 2

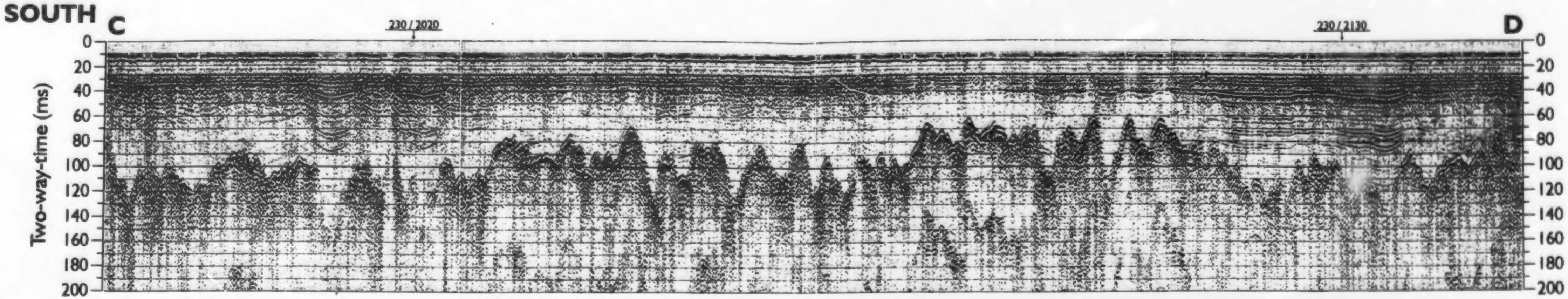
Distance (km)



NB10 sheet 1 of 2 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES

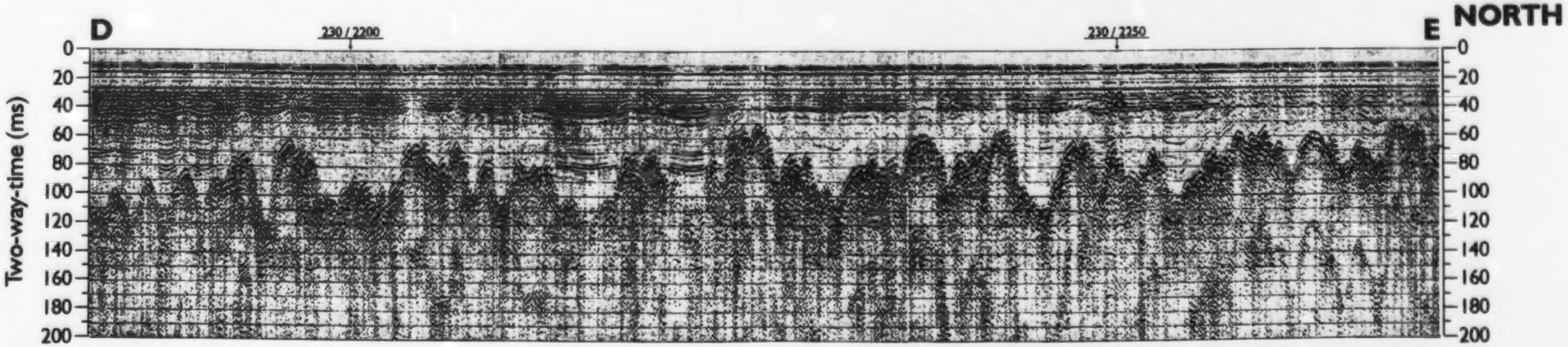
NORTH BASIN LINE 10



V.E. (@1500 m/s) = 11.6X

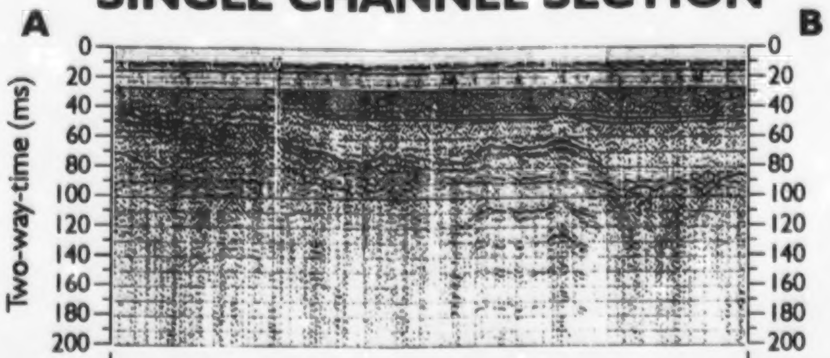
0 1 2

Distance (km)



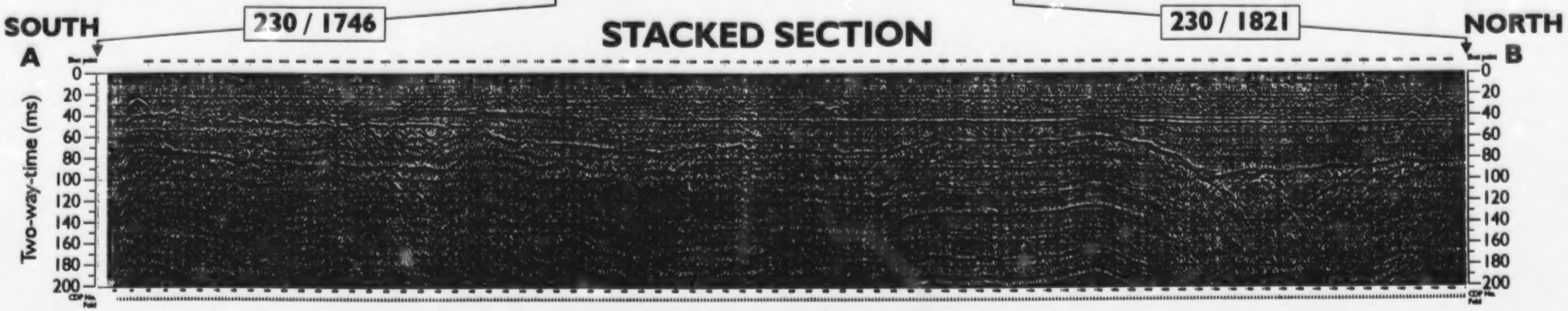
LAKE WINNIPEG PROJECT LINE NB10: MULTICHANNEL SEISMIC PROCESSING

SINGLE CHANNEL SECTION

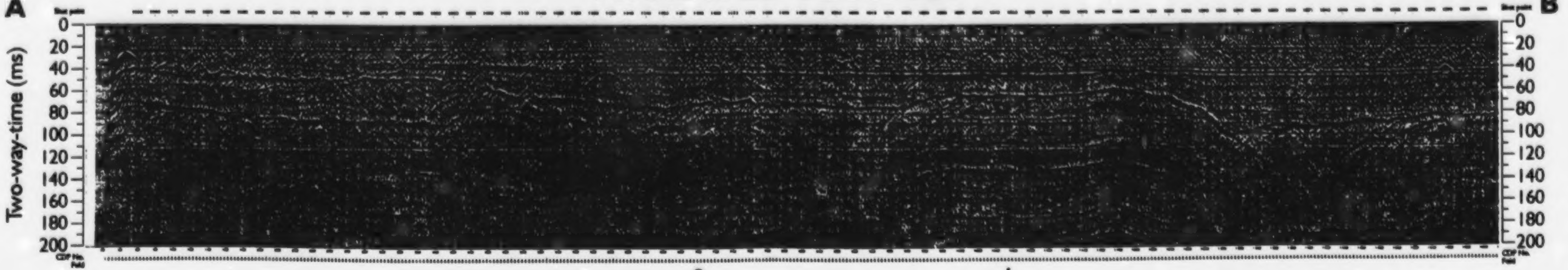


Single Channel V.E. (@1500 m/s)=14.2X

STACKED SECTION



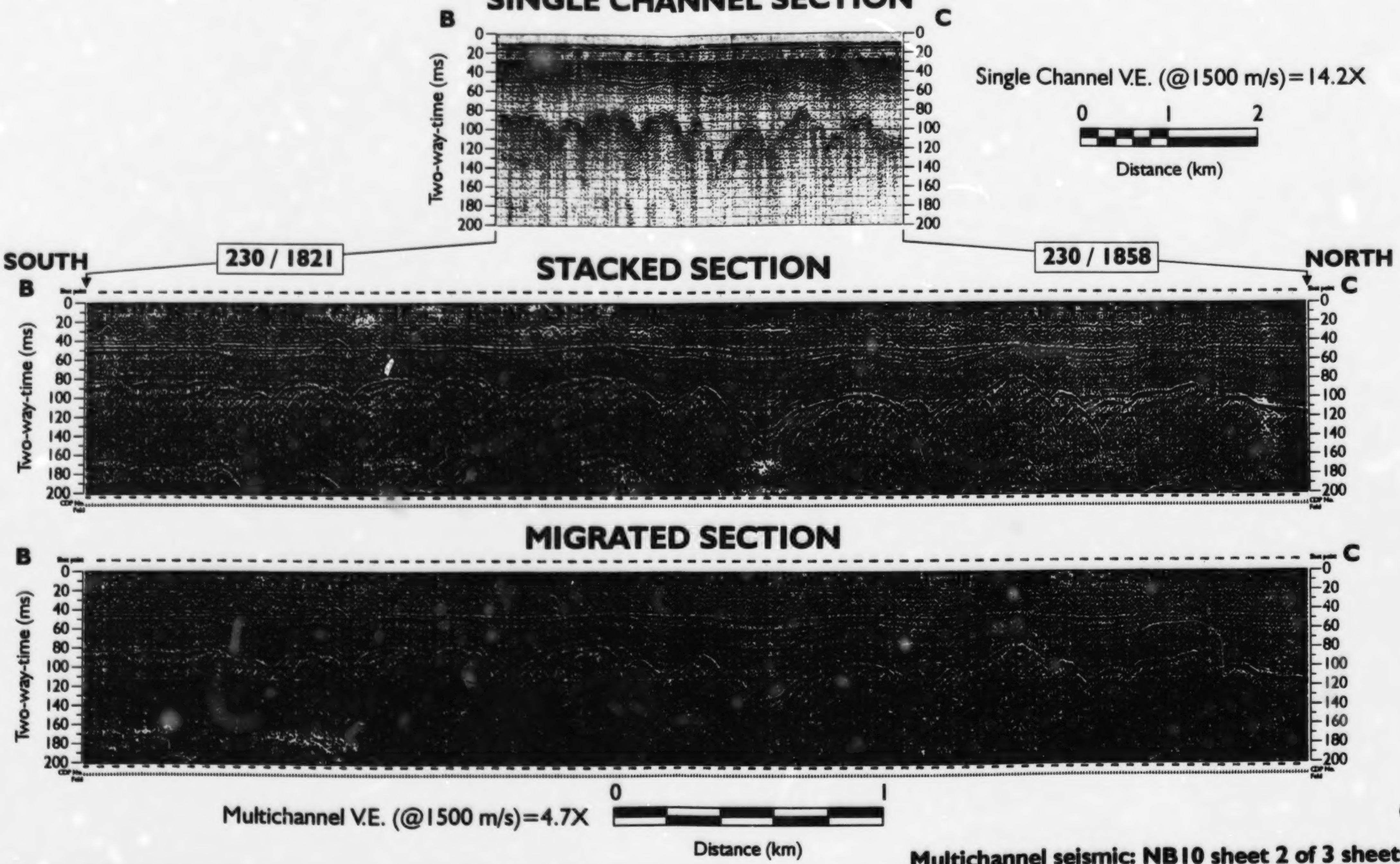
MIGRATED SECTION



Multichannel V.E. (@1500 m/s)=4.7X

Multichannel seismic: NB10 sheet 1 of 3 sheets

LAKE WINNIPEG PROJECT LINE NB10: MULTICHANNEL SEISMIC PROCESSING



SINGLE CHANNEL SECTION

Single Channel V.E. (@1500 m/s)=14.2X

STACKED SECTION

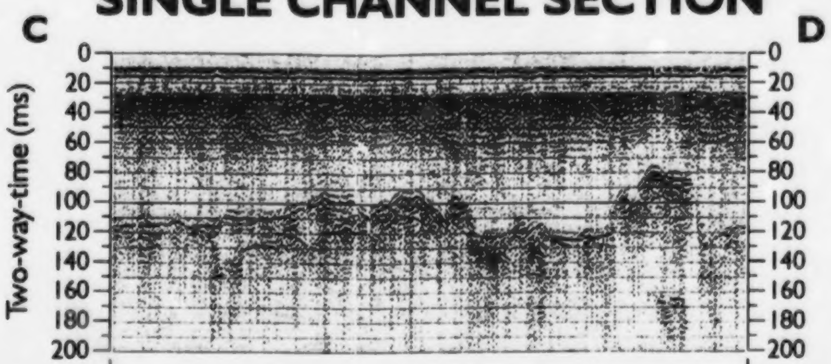
MIGRATED SECTION

Multichannel V.E. (@1500 m/s)=4.7X

Multichannel seismic: NB10 sheet 2 of 3 sheets

LAKE WINNIPEG PROJECT LINE NB10: MULTICHANNEL SEISMIC PROCESSING

SINGLE CHANNEL SECTION



Single Channel V.E. (@1500 m/s)=14.2X

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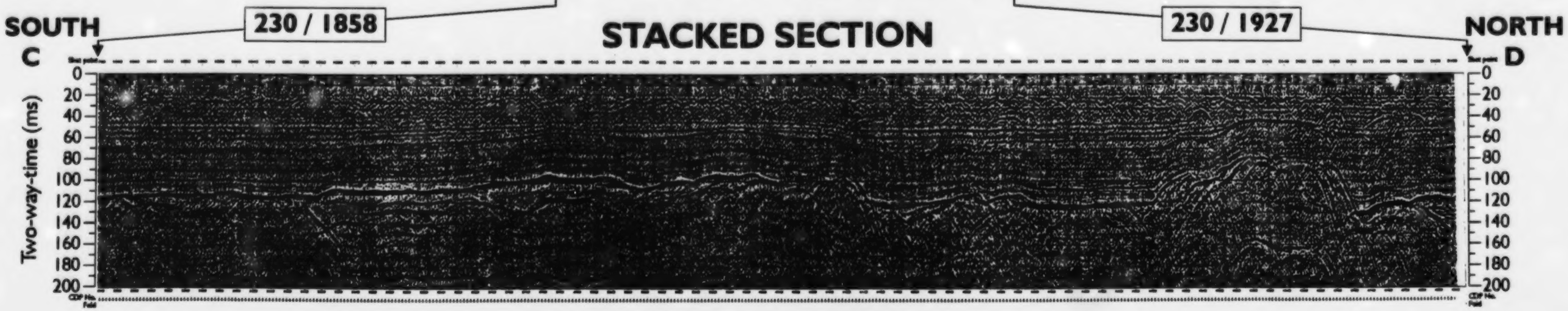
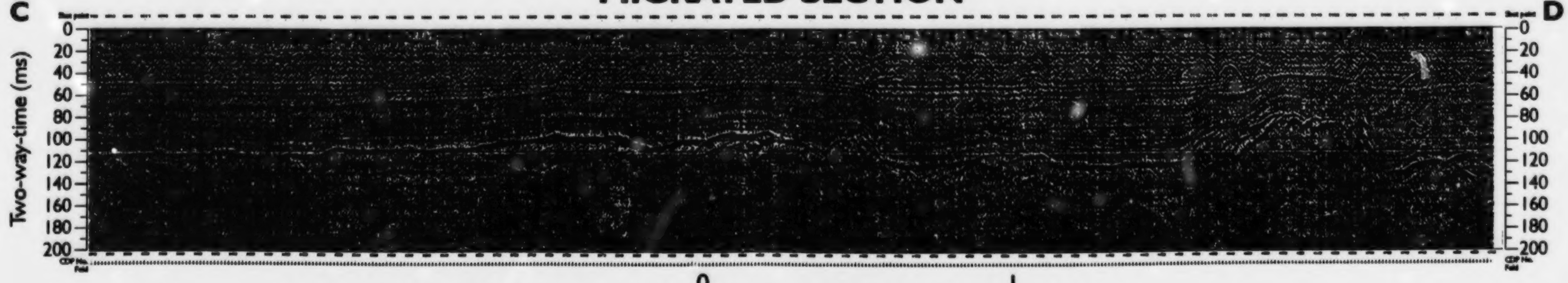


MIGRATED SECTION



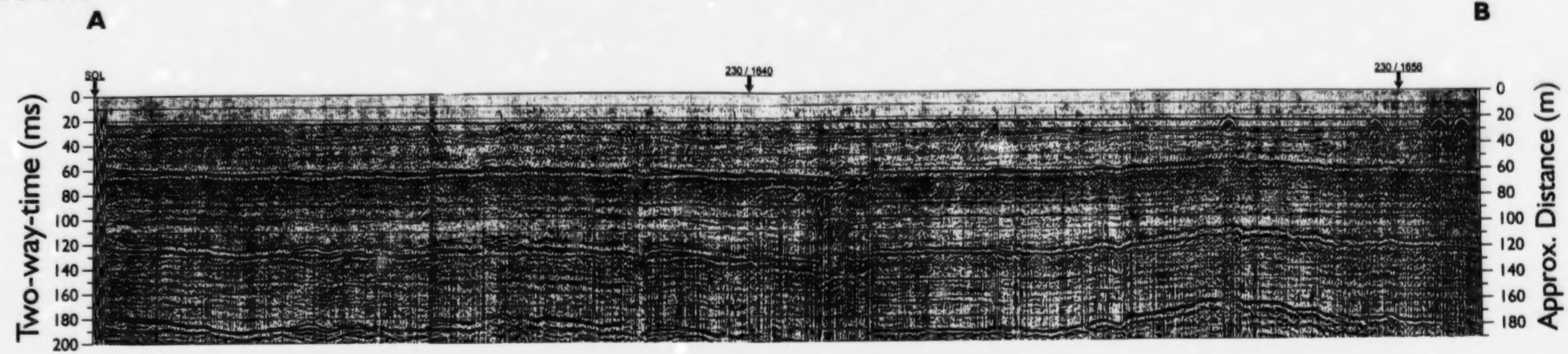
Multichannel V.E. (@1500 m/s)=4.7X

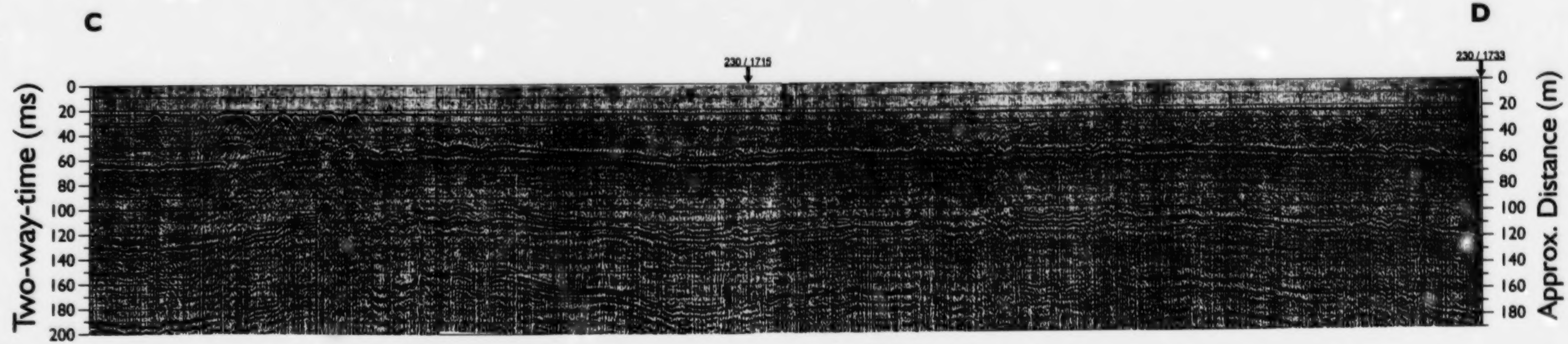
Multichannel seismic: NB10 sheet 3 of 3 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

NORTH BASIN LINE 10
SINGLE FOLD CDP

SOUTH





V.E.~4X

0 0.5 1

Approximate Distance (km)

NB10 sheet 1 of 6 sheets

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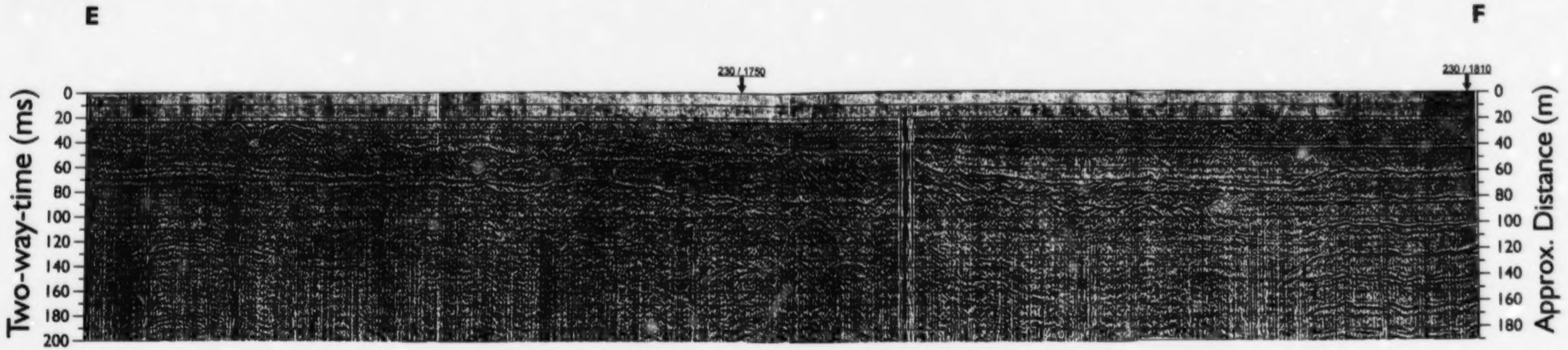
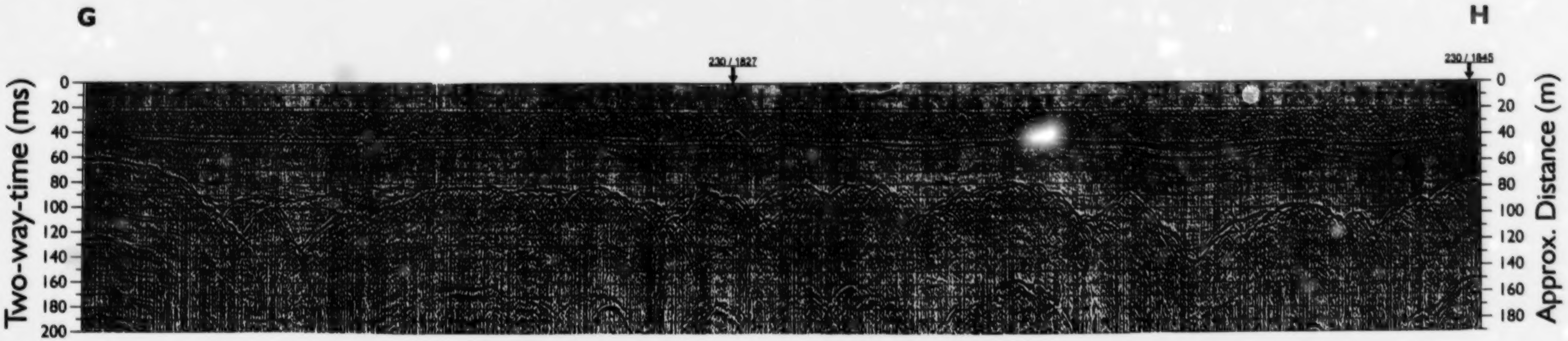
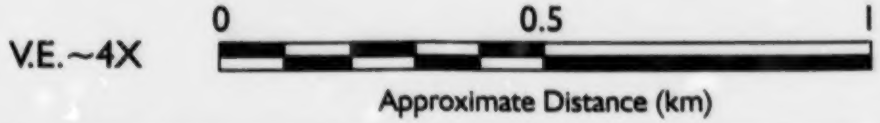
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

NORTH BASIN LINE 10
SINGLE FOLD CDP

SOUTH



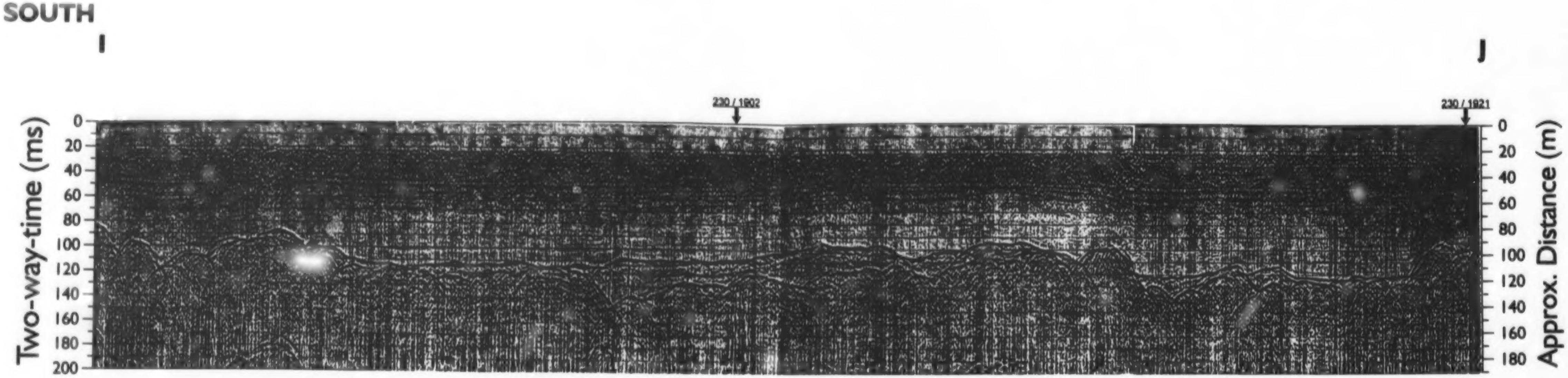


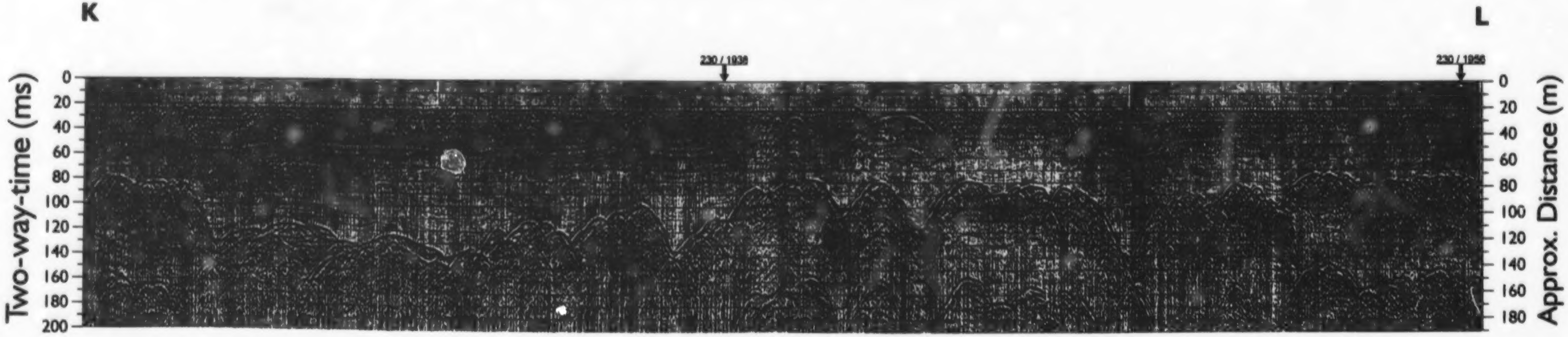

V.E.~4X
0
0.5
1
Approximate Distance (km)

LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

NORTH BASIN LINE 10
SINGLE FOLD CDP

SOUTH





V.E.~4X

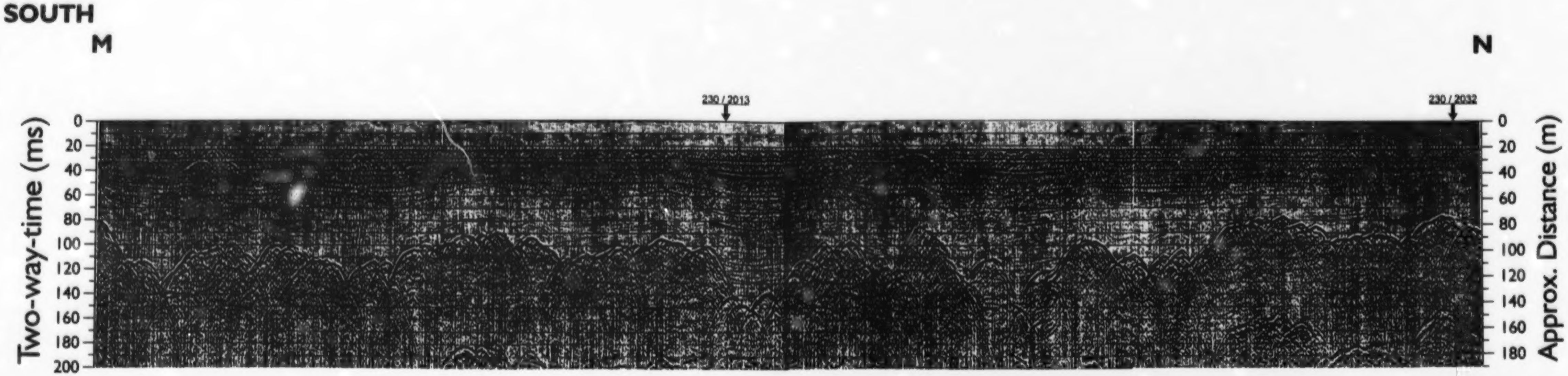
0 0.5 1

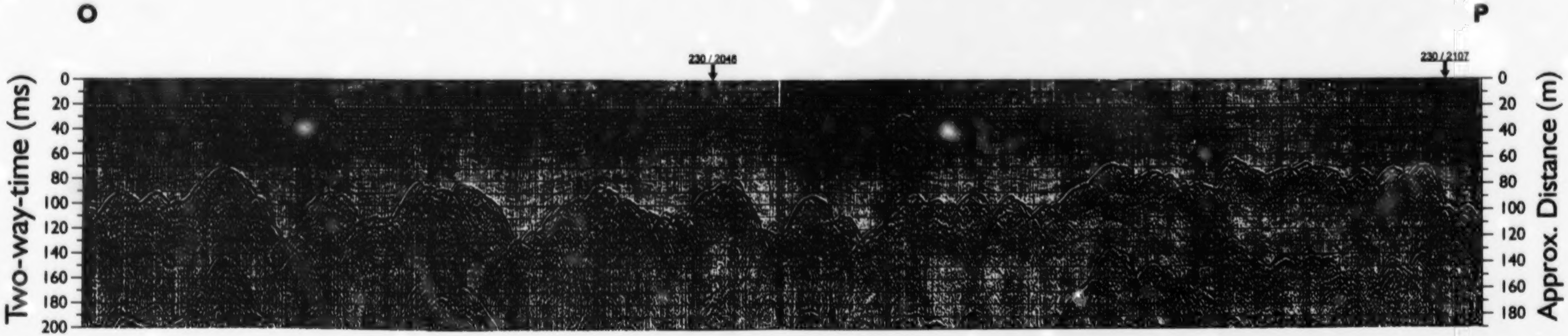
Approximate Distance (km)

NB10 sheet 3 of 6 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

NORTH BASIN LINE 10
SINGLE FOLD CDP





V.E.~4X

0 0.5 1

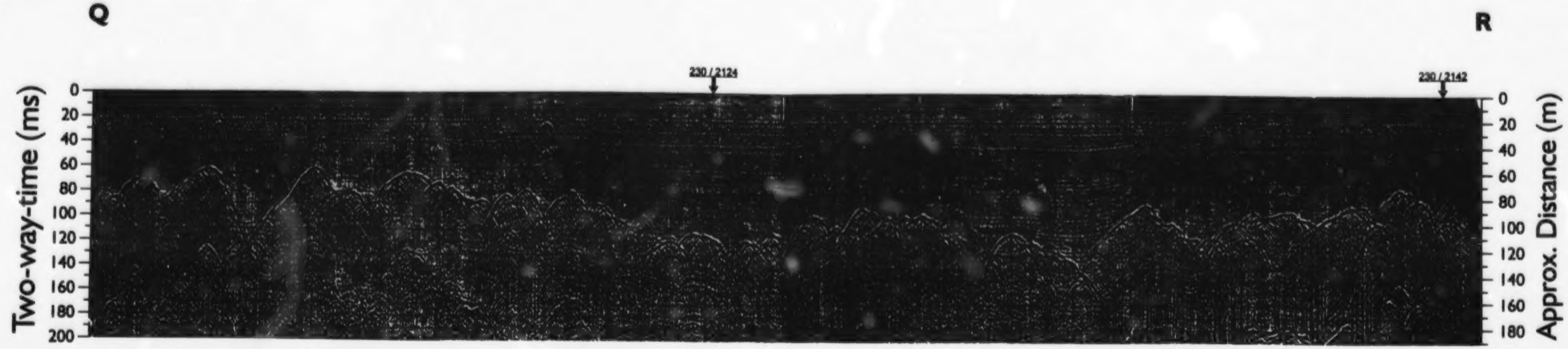
Approximate Distance (km)

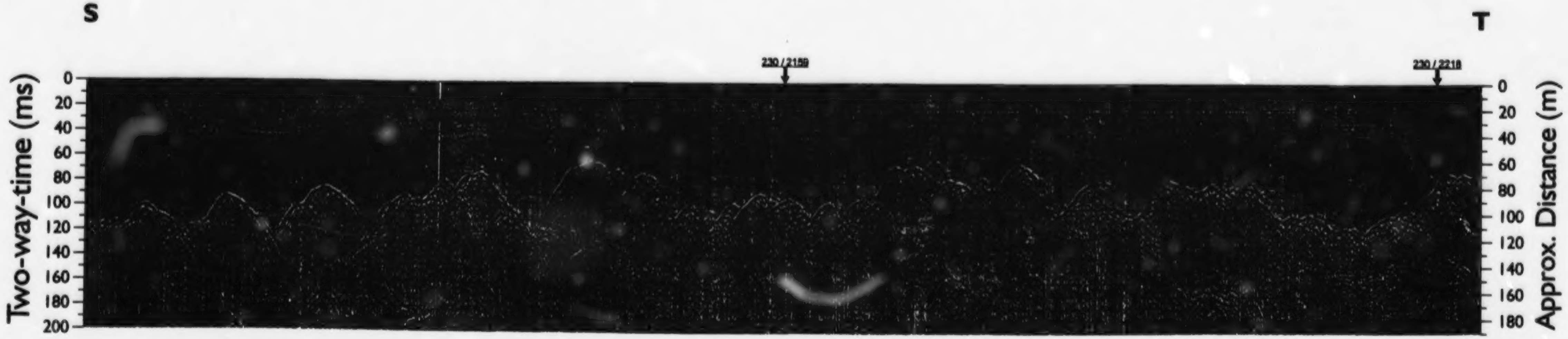
NB10 sheet 4 of 6 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

NORTH BASIN LINE 10
SINGLE FOLD CDP

SOUTH





V.E.~4X

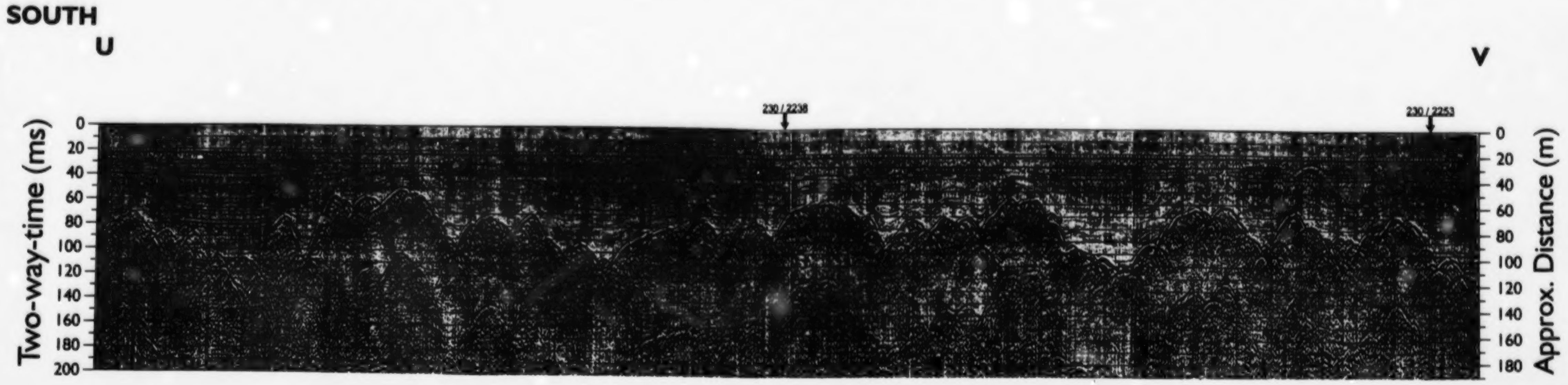
0 0.5 1

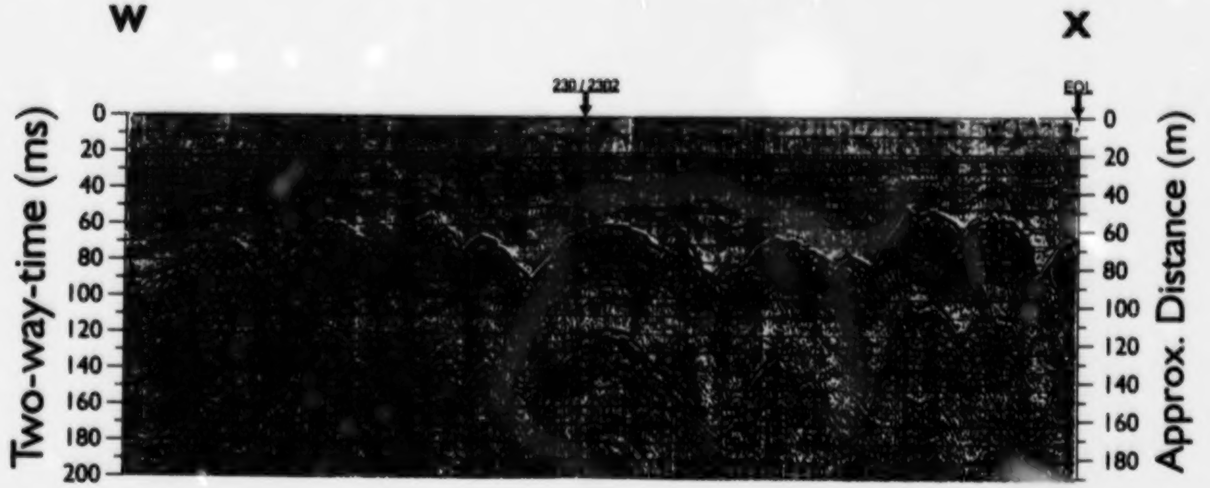
Approximate Distance (km)

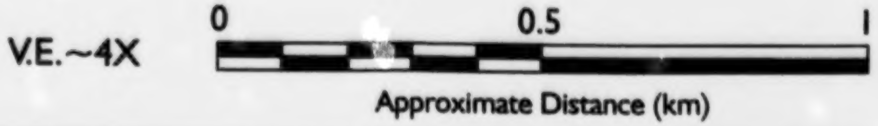
NB10 sheet 5 of 6 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

NORTH BASIN LINE 10
SINGLE FOLD CDP



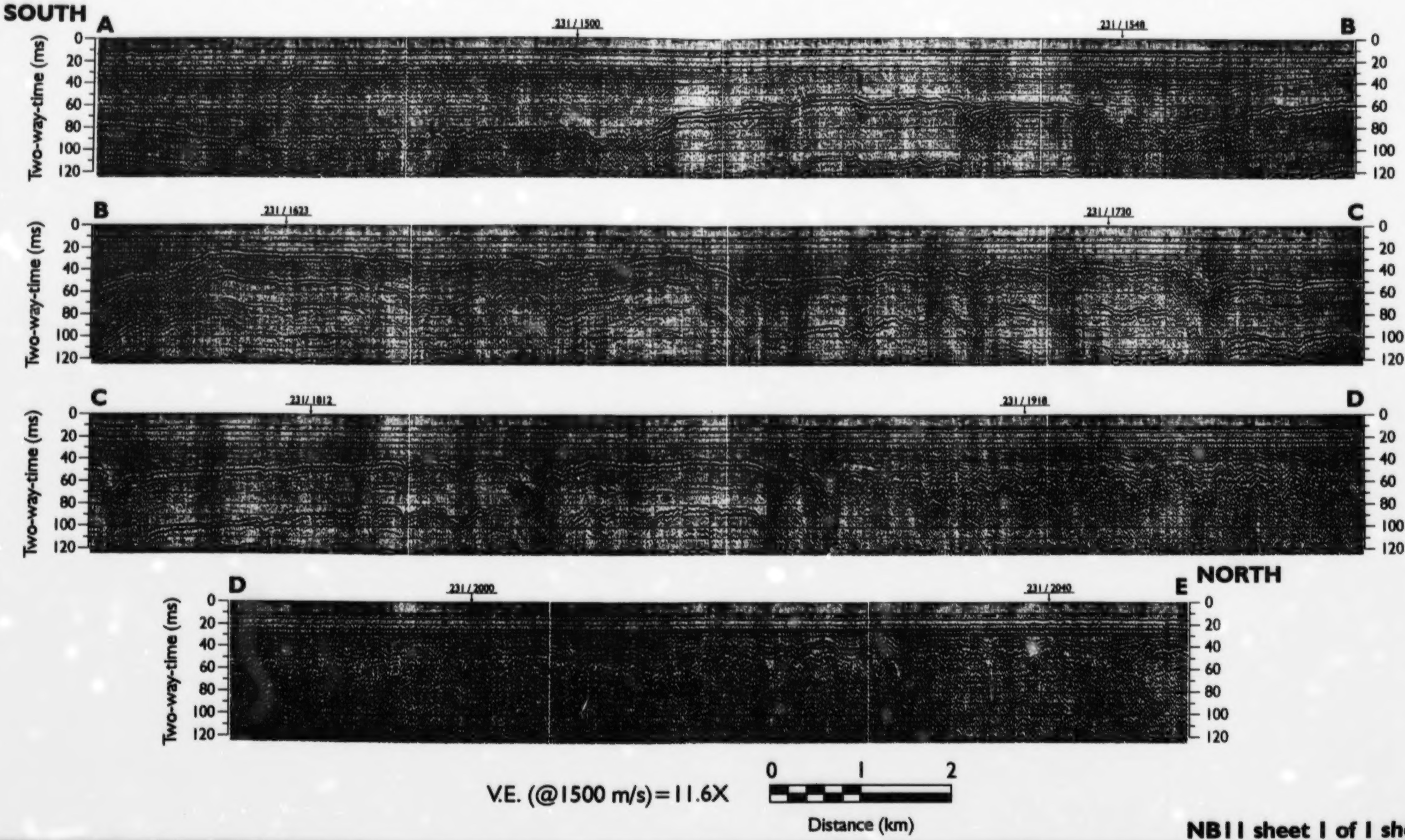



V.E.~4X
0
0.5
1
Approximate Distance (km)

NB10 sheet 6 of 6 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES

NORTH BASIN LINE 11



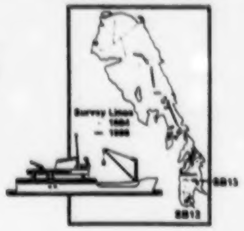
V.E. (@1500 m/s) = 11.6X

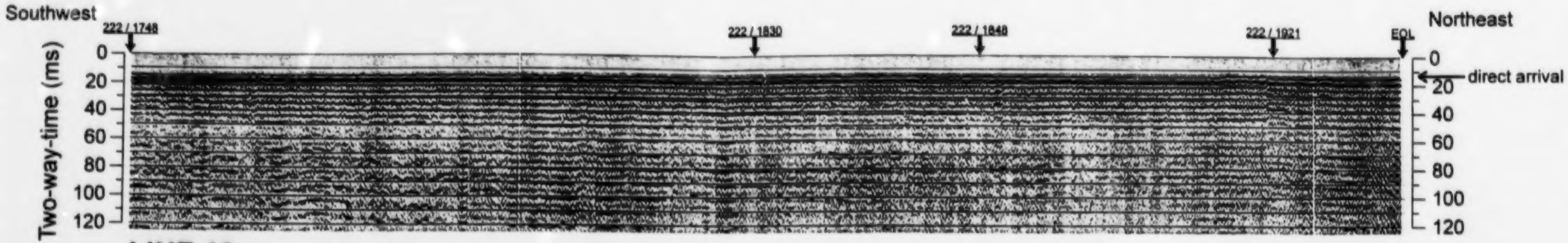
NB11 sheet 1 of 1 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

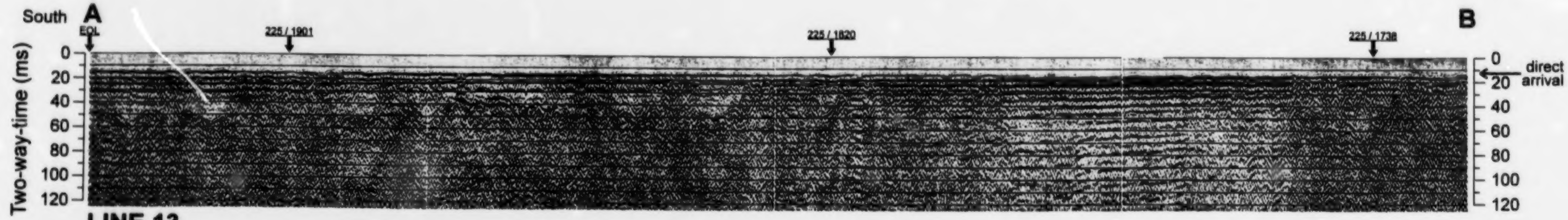
(Common offset gathers from multichannel data: offset = 20 m)

SOUTH BASIN: LINE 12 AND LINE 13

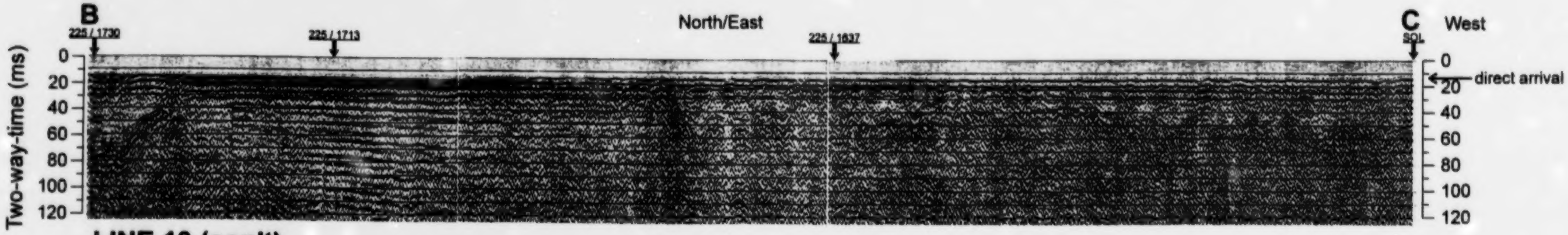

Survey Lines
SB13
SB12



LINE 12



LINE 13



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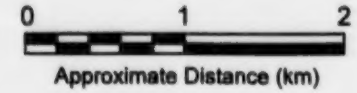
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Approximate Distance (km)

SB12 & SB13 sheet 1 of 1 sheets

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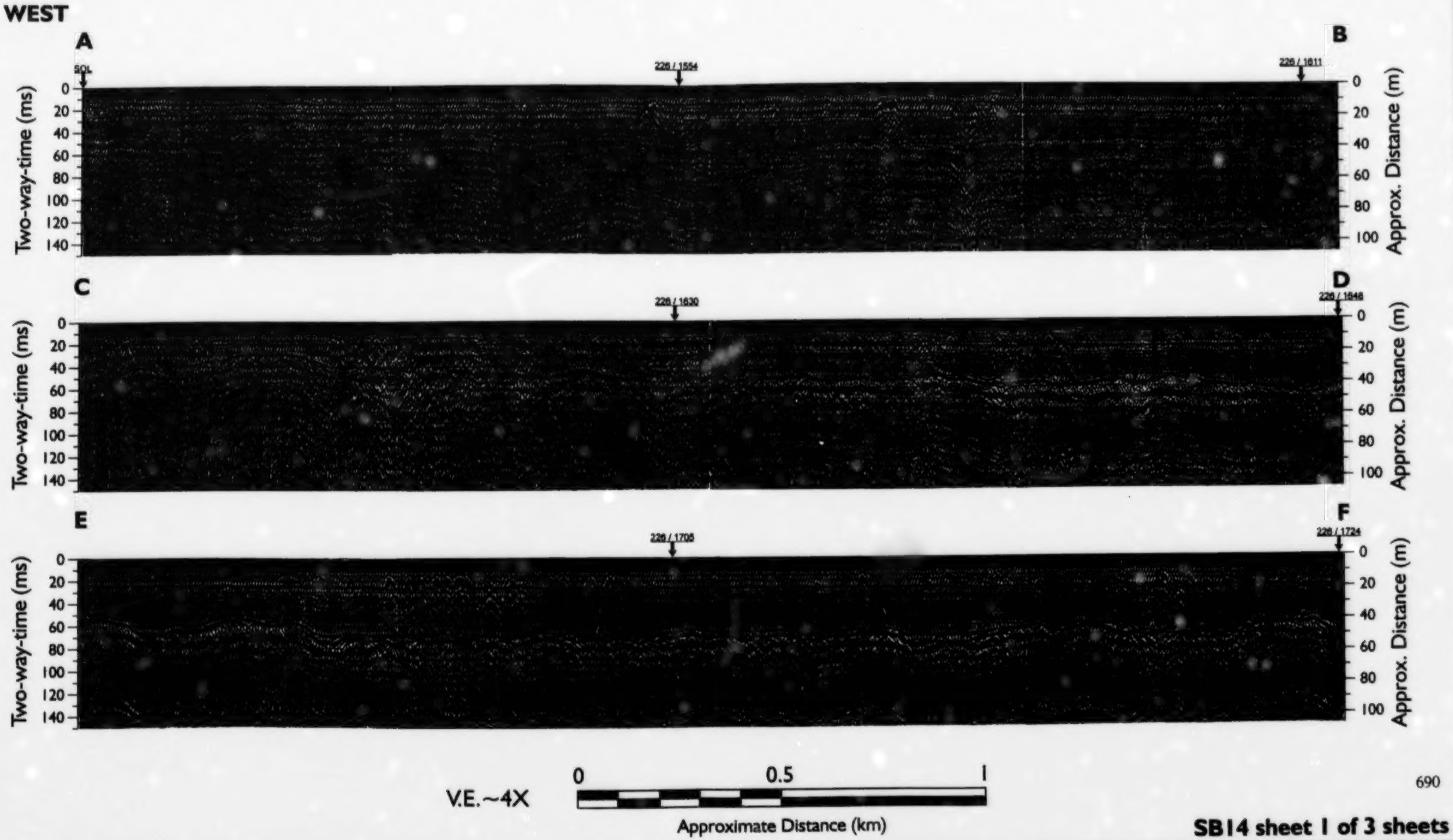
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

SOUTH BASIN LINE 14



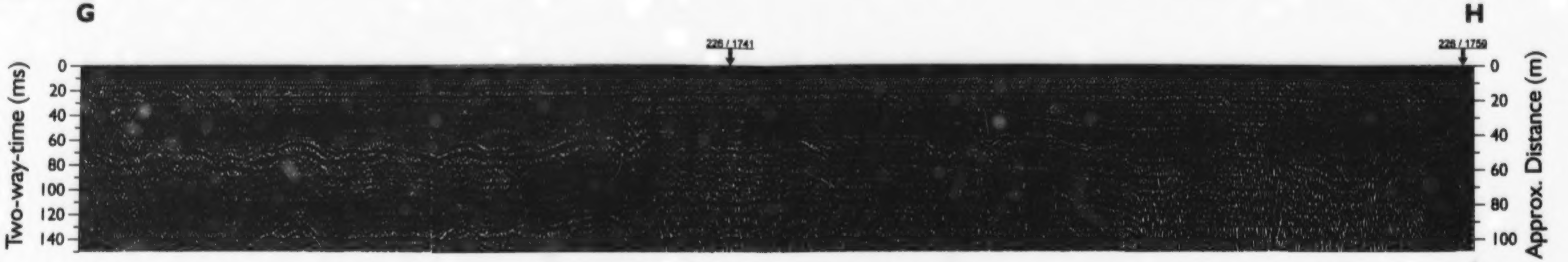
SB14 sheet 1 of 3 sheets

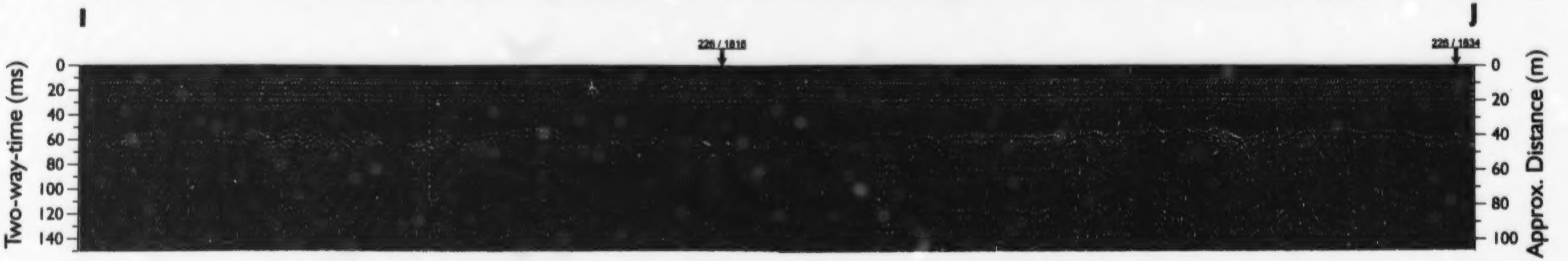
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

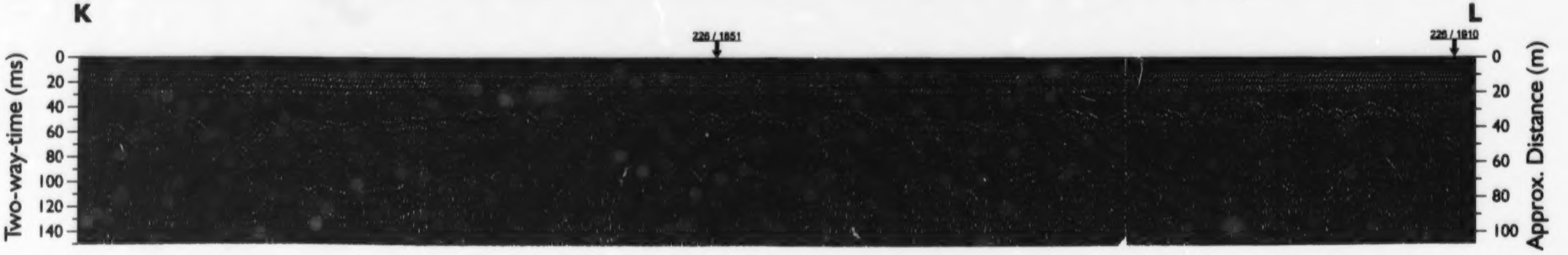
SOUTH BASIN LINE 14

Survey Lines

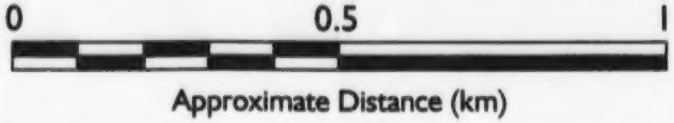
WEST







V.E.~4X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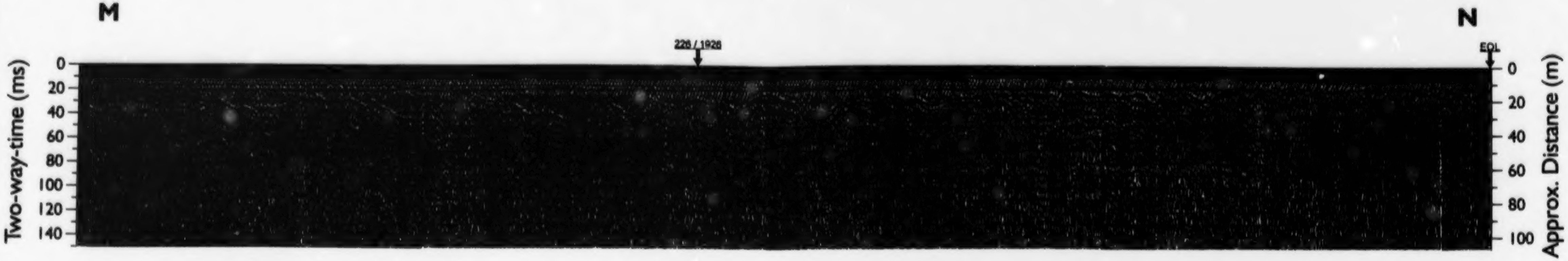
Approximate Distance (km)

SB14 sheet 2 of 3 sheets

LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

SOUTH BASIN LINE 14

WEST



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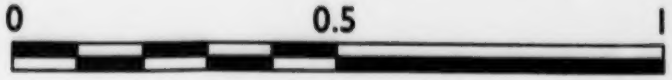


Approximate Distance (km)

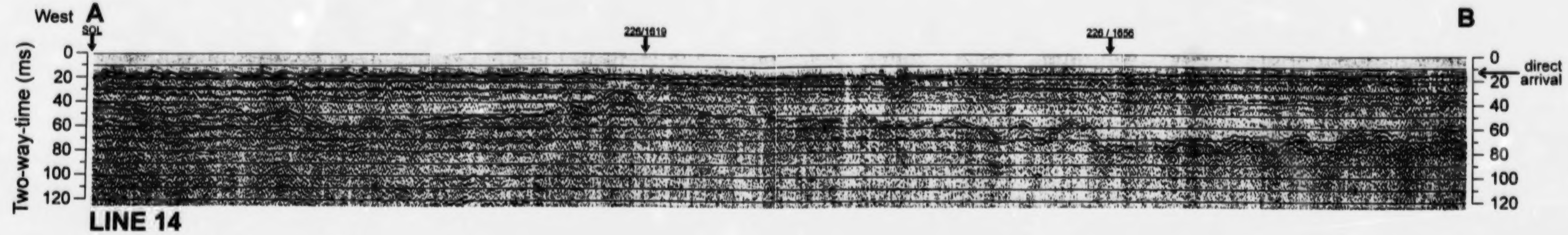
SB14 sheet 3 of 3 sheets

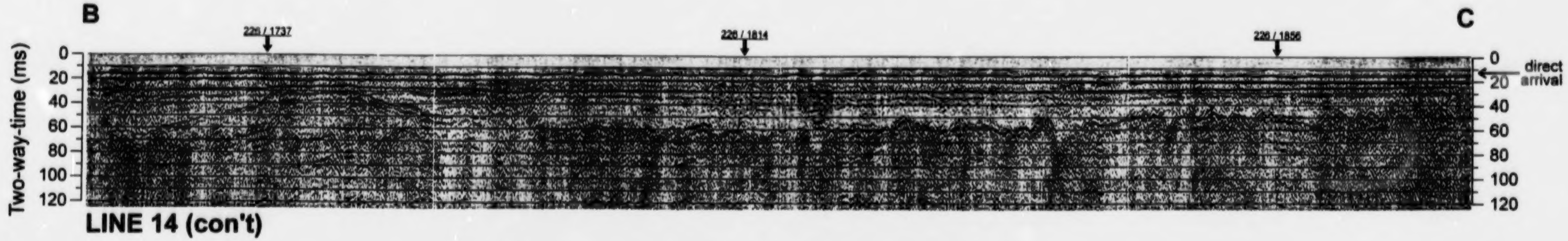
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

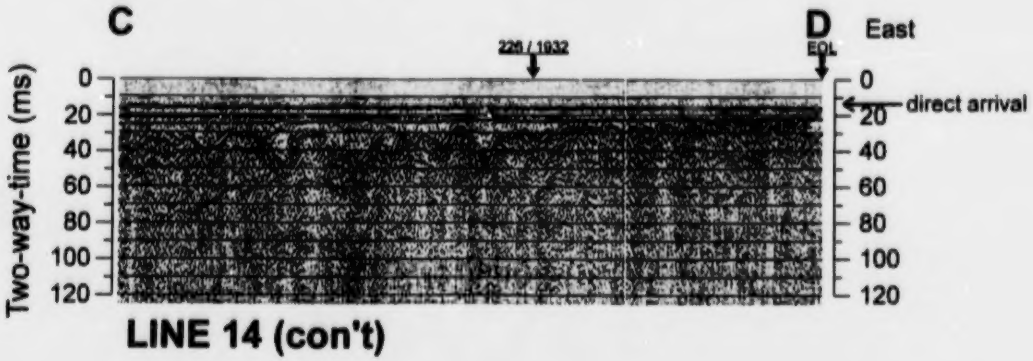
(Common offset gathers from multichannel data: offset = 20 m)

SOUTH BASIN: LINE 14

Survey Lines
SB14







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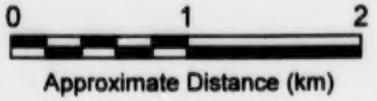
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2
Approximate Distance (km)

SB14 sheet 1 of 1 sheets

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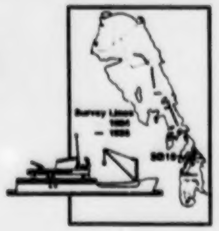
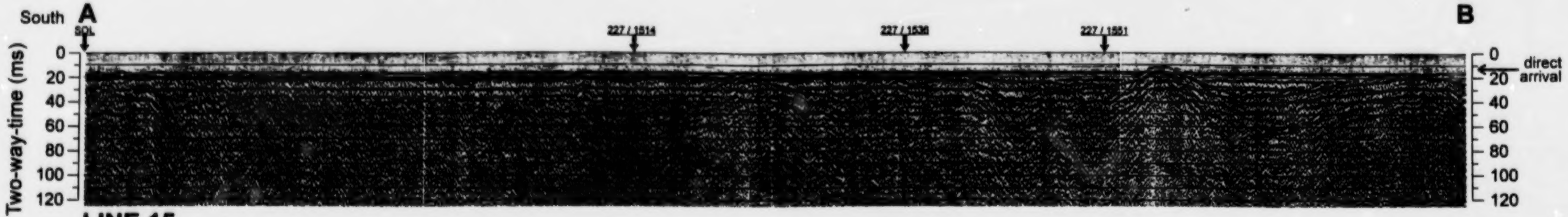
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

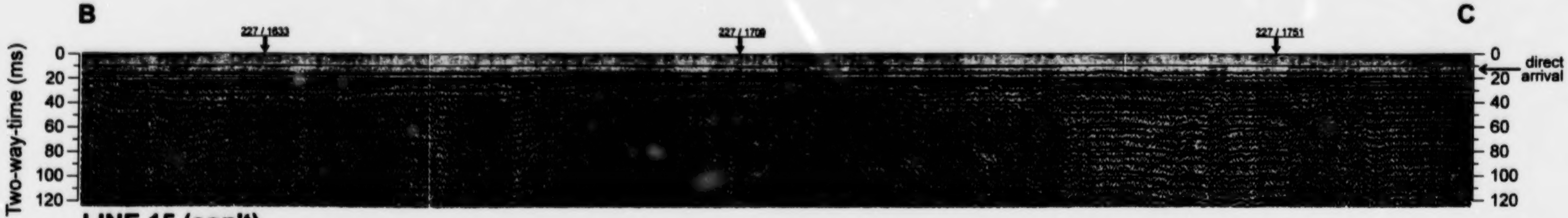
(Common offset gathers from multichannel data: offset = 20 m)

SOUTH BASIN: LINE 15

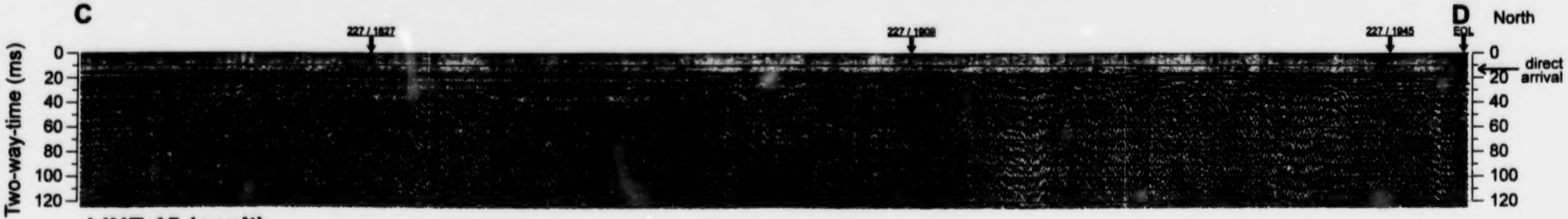

Survey Lines
1994
1996



LINE 15



LINE 15 (con't)



LINE 15 (con't)

trace spacing ~ 10 m
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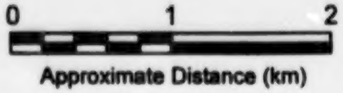
0
1
2
Approximate Distance (km)

SB15 sheet 1 of 1 sheets

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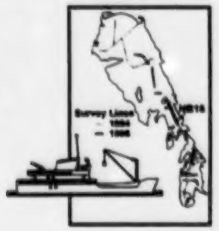
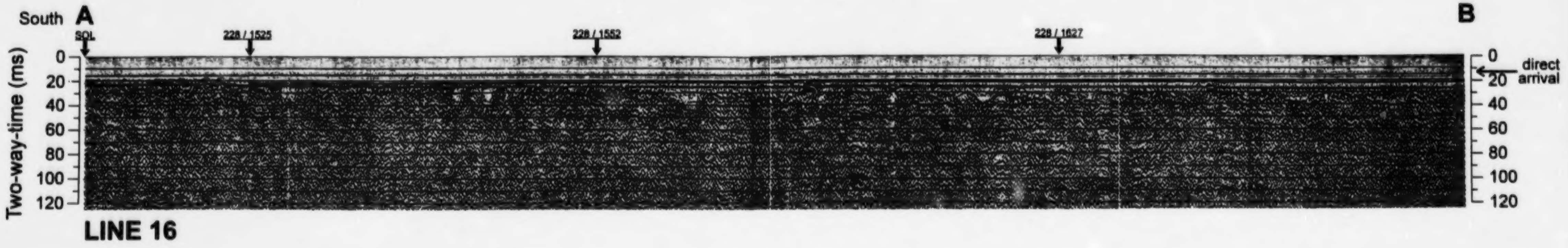
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

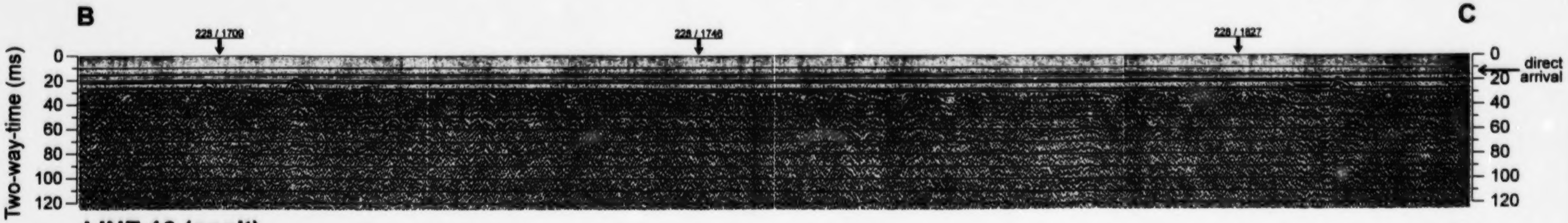
(Common offset gathers from multichannel data: offset = 20 m)

NORTH BASIN: LINE 16


Survey Lines
1994
1996
NB16



LINE 16



LINE 16 (con't)

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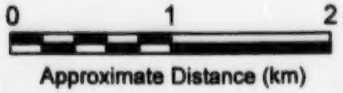
0
1
2
Approximate Distance (km)

NB16 sheet 1 of 2 sheets

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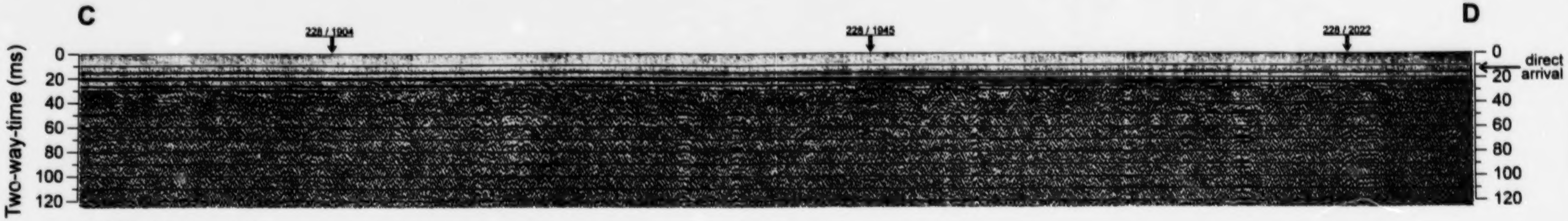
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

(Common offset gathers from multichannel data: offset = 20 m)

NORTH BASIN: LINE 16

Survey Lines
NB16



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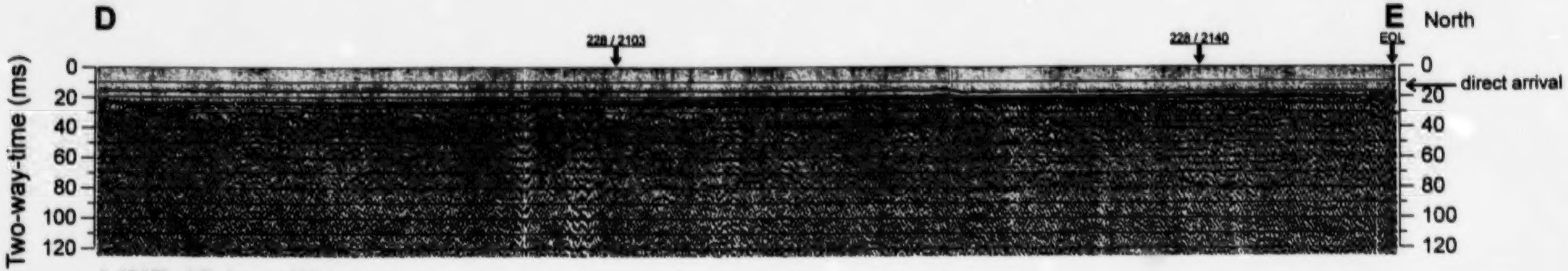
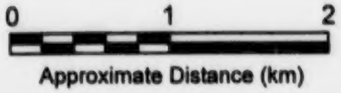


LINE 16 (con't)

trace spacing ~ 10 m
vertical exaggeration (@1500 m/s) ~ 15x


0
1
2
Approximate Distance (km)

NB16 sheet 2 of 2 sheets

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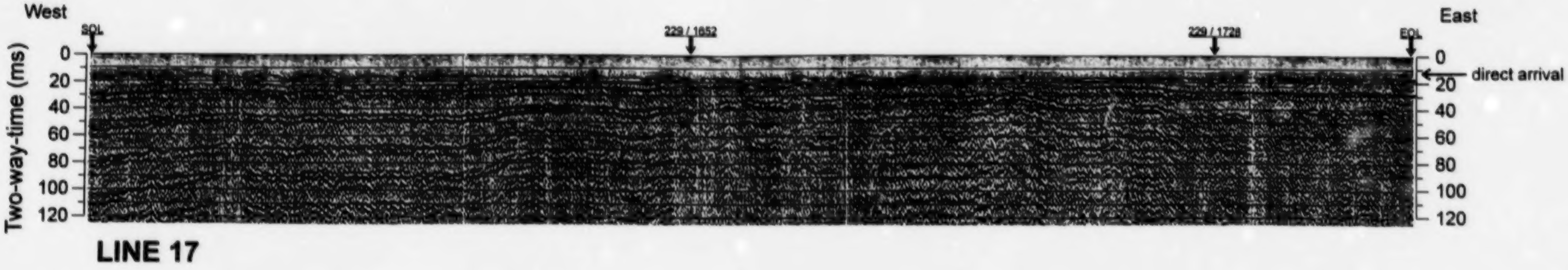
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

(Common offset gathers from multichannel data: offset = 20 m)

NORTH BASIN: LINE 17



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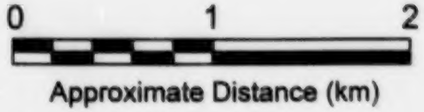

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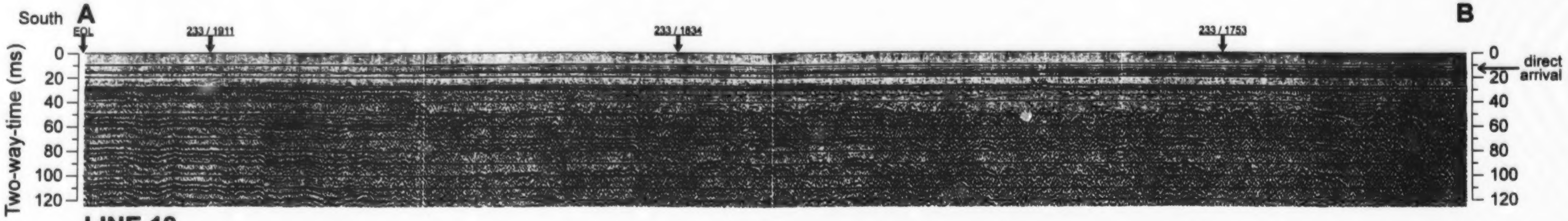
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

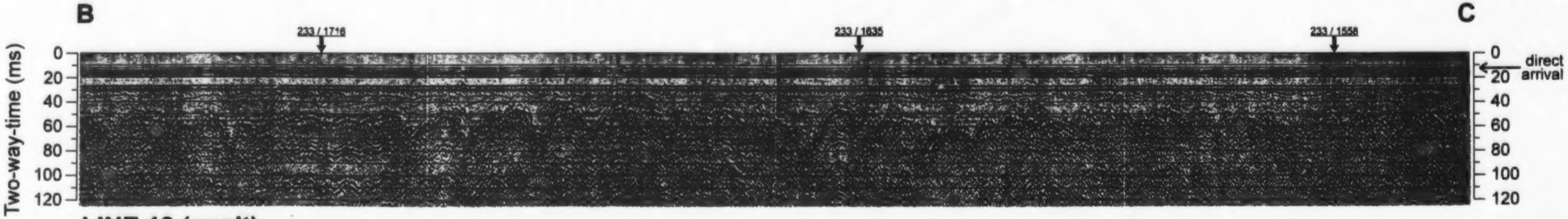
(Common offset gathers from multichannel data: offset = 20 m)

NORTH BASIN: LINE 18

NB18
Survey Lines



LINE 18



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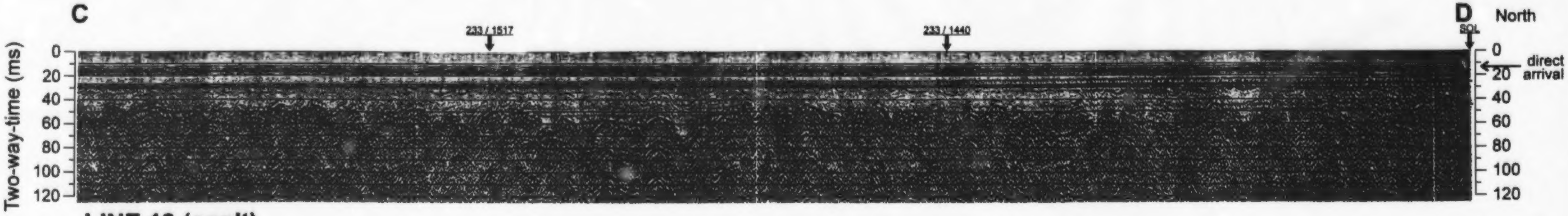

LINE 18 (con't)

trace spacing ~ 9 m
vertical exaggeration (@1500 m/s) ~ 14x

0 1 2
Approximate Distance (km)

698

NB18 sheet 1 of 1 sheets

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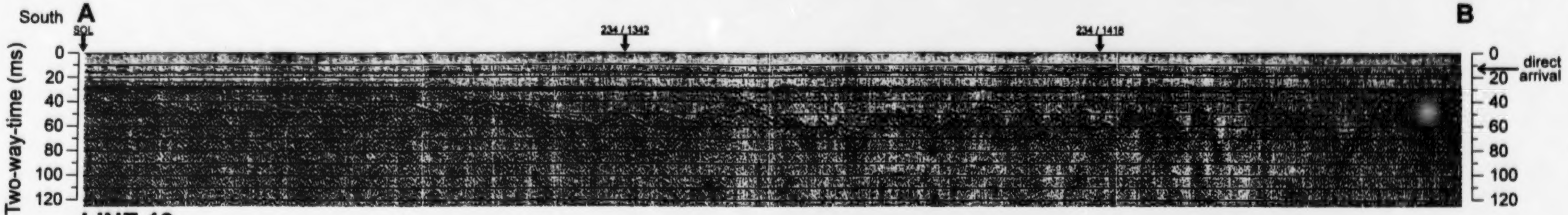
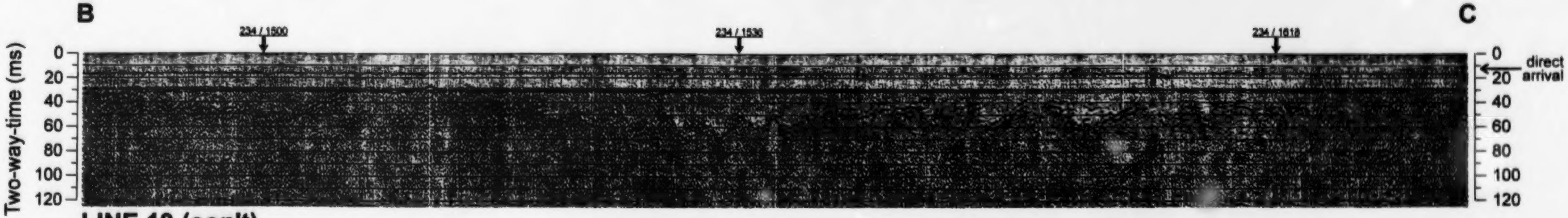
LAKE WINNIPEG PROJECT SEISMIC PROFILES 1996

(Common offset gathers from multichannel data: offset = 20 m)

NORTH BASIN: LINE 19



LINE 19



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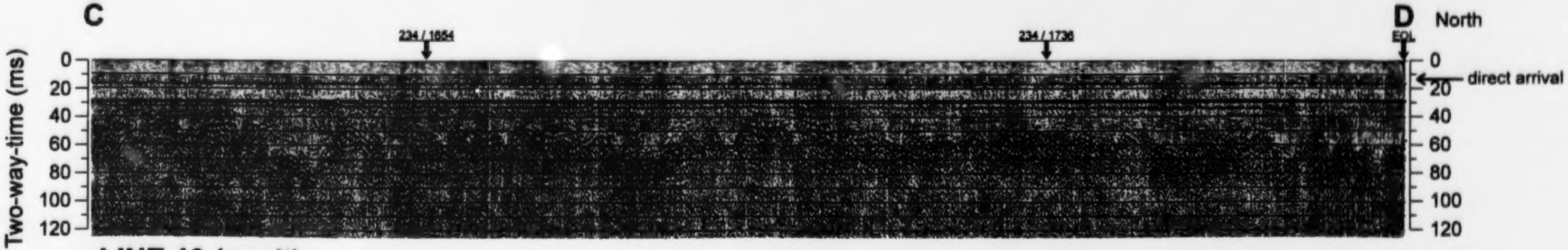

LINE 19 (con't)

trace spacing ~ 10 m
vertical exaggeration (@1500 m/s) ~ 15x

0 1 2
Approximate Distance (km)

NB19 sheet 1 of 1 sheets

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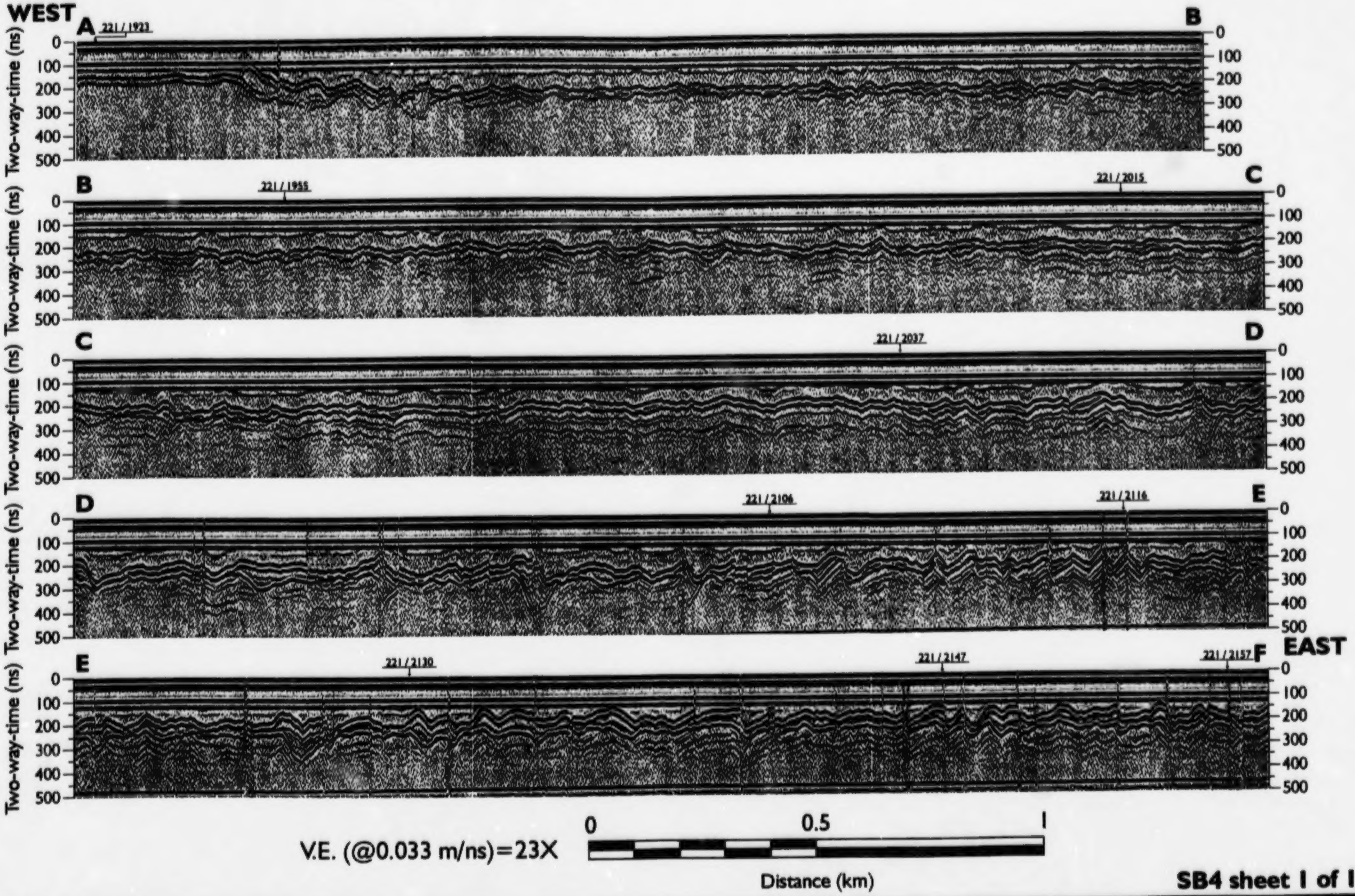
LAKE WINNIPEG PROJECT RADAR PROFILE

SOUTH BASIN LINE 4



700

SB4 sheet 1 of 1 sheets

Appendix 10.6

Lake Winnipeg Project radiocarbon dates

A.M. Telka

Geological Survey of Canada (Ottawa)

INTRODUCTION

The following date list and index tables document radiocarbon ages determined as part of the Lake Winnipeg Project on 39 samples from offshore cores, 8 samples from nearshore cores, 6 samples from onshore core or auger samples, 21 samples of wood from the shore zone, and 9 samples of other shore-zone materials. Two earlier age determinations on peat from Elk Island (Penner and Swedlo, 1974) are also included. Offshore core materials from the Lake Winnipeg Project were collected onboard CCGS *Namao* during cruises 94900 and 96900 in 1994 and 1996 respectively (Todd et al., 1996; Todd, this volume; Lewis et al., this volume). Nearshore cores were collected through the ice in March 1997 (Forbes, in prep.). Onshore cores include auger samples from Netley Marsh and Willow Point marsh (Nielsen, 1998) and Hiller cores from Limestone Bay and Passage Point (Forbes and Frobel, 1996). Other onshore samples include shell material, peat and organic-rich deposits in the shore zone, and wood (either driftwood or more commonly stumps in-situ) collected from the shallow nearshore, beach, or backshore (Nielsen and Conley, 1994; Nielsen, 1998, this volume).

Macrofossil specimens from cores were separated and identified by Vance and Telka (1998) and Telka (this volume). Other shell and wood specimens were identified by E. Nielsen and colleagues. While some of these samples (BETA, BGS, and GSC series) were submitted for conventional radiocarbon analysis, most (CAMS series) were dated by accelerator mass spectrometry (AMS) on small specimens (Telka, this volume). The first table gives offshore samples in order of core number and depth in core. The second table lists nearshore and onshore samples by group and geographic locality. These tables provide an index to the date list, which is arranged alphabetically and numerically by radiocarbon laboratory number. Plant and Insect Macrofossil Reports cited in the date list can be found in the forthcoming Manitoba Date List (Morlan et al., 2000).

Abbreviations used in the following tables:

Laboratories

BETA: Beta Analytic Inc.
BGS: Brock University (Geological Sciences)
CAMS: Lawrence Livermore National Laboratory (Center for Accelerator Mass Spectrometry)
GSC: Geological Survey of Canada

Affiliations

GSC Geological Survey of Canada
MGSB Manitoba Geological Services Branch

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Table 1. Lake Winnipeg offshore radiocarbon dates

Site/ Sample Number	Lab Number	Age (^{14}C yr BP)	Taxon
94900 LW 104aGC 237-243 cm	CAMS-32189	7700 ± 50	twigs
94900 LW 106PC 176-182 cm	CAMS-32191	6910 ± 200	ostracodes
94900 LW 106PC 174-179 cm	CAMS-38675	6900 ± 80	ostracodes
94900 LW 115GC 256-263 cm	CAMS-32190	3060 ± 70	twig
94900 LW 122aGC 425-433 cm	CAMS-17434	4040 ± 70	*Scirpus* sp. seed
94900 LW 122aGC 17-23 cm	CAMS-19445	3990 ± 50	bulk sediment
94900 LW 122aGC 118-123 cm	CAMS-19446	5820 ± 50	bulk sediment
94900 LW 122aGC 188-192 cm	CAMS-19447	6900 ± 60	bulk sediment
94900 LW 122aGC 268.5-272 cm	CAMS-19448	7570 ± 50	bulk sediment
94900 LW 122aGC 318.5-322 cm	CAMS-19449	7560 ± 70	bulk sediment
94900 LW 122aGC 388.5-392 cm	BETA-81335	11050 ± 270	bulk sediment
96900 LW 201PC 434-439	CAMS-35499	4800 ± 70	*Picea* sp. needles
96900 LW 202PC 174-179 cm	CAMS-32192	6870 ±60	ostracodes
96900 LW 204PC 362-373 cm	CAMS-38676	6700 ± 80	ostracodes
96900 LW 204PC 513-518 cm	CAMS-38678	6750 ± 70	*Picea* sp. needles
96900 LW 207PC 155-163 cm	CAMS-38677	9170 ± 70	ostracodes
96900 LW 209PC 95-97cm	CAMS-35497	3730 ± 70	*Juniperus communis* L. seed
96900 LW 213PC 10-15 cm	CAMS-46187	2540 ± 60	*Picea* sp. needle
96900 LW 214PC 298-303 cm	CAMS-38679	3630 ± 50	wood
96900 LW 215PC 321.5 cm	CAMS-34554	3950 ± 60	*Scirpus* sp. seed
96900 LW 215PC 348 cm	CAMS-34555	4030 ± 50	*Scirpus* sp. seed
96900 LW 217PC 127-132 cm	CAMS-35498	3340 ± 50	*Scirpus* sp. seed
96900 LW 217PC 135-140 cm	CAMS-46190	3340 ± 40	*Scirpus* sp. seeds
96900 LW 217PC 253-257 cm	CAMS-46191	3910 ± 60	*Chenopodium* sp. seeds
96900 LW 219PC 372-377 cm	CAMS-35494	1970 ± 170	terrestrial insect parts
96900 LW 219PC 436-439 cm	CAMS-35500	2940 ± 80	*Rubus idaeus* L. seeds
96900 LW 220PC 395-400 cm	CAMS-46193	3870 ± 140	*Polygonum amphibium* L. seed
96900 LW 220PC 535-540 cm	CAMS-35495	3920 ± 70	*Chenopodium* sp. seeds
96900 LW 220PC 542-547 cm	CAMS-32193	4760 ± 70	shell
96900 LW 221PC 523-528 cm	CAMS-38680	4190 ± 100	*Scirpus* sp. seed
96900 LW 221PC 526-527 cm	CAMS-35616	4320 ± 50	*Sphaerium striatinum* shell
96900 LW 222PC 735-740 cm	CAMS-46188	4710 ± 50	*Scirpus* sp. seed
96900 LW 223PC 507-509 cm	CAMS-34550	3280 ± 60	*Scirpus* sp. seed
96900 LW 223PC 661-666 cm	CAMS-34551	4000 ± 60	*Scirpus* sp. seed
96900 LW 223PC 721-726 cm	CAMS-46186	4030 ± 50	*Scirpus* sp. seed
96900 LW 224PC 577-582 cm	CAMS-35496	3550 ± 70	*Helianthus* sp. seed
96900 LW 224PC 577-582 cm	CAMS-35501	3570 ± 120	*Scirpus* sp. seeds
96900 LW 224PC 584-589 cm	CAMS-46192	5350 ± 50	*Scirpus* sp. seed
96900 LW 224PC 705-710 cm	CAMS-35615	4090± 60	shell

Table 2. Lake Winnipeg shore-zone radiocarbon dates

Site/ Sample Number	Lab Number	Age (^{14}C yr BP)	Taxon
Limestone Bay 94307-003 70-79 cm	CAMS-34553	930 ± 90	*Potentilla norvegica* L. seeds
Passage Point 94307-010 132-142 cm	CAMS-34552	1020 ± 50	*Salix* twig
Disbrowe Point 97301-007	CAMS-44526	modern	*Rubus ideas* L. seeds
Disbrowe Point 97301-008 5-7 cm	CAMS-44527	2510 ± 50	twig
Disbrowe Point 97301-008 33-34 cm	CAMS-44528	2910 ± 50	*Mentha* sp. seeds
Hecla Island 97301-010 13 cm	CAMS-46189	2190 ± 50	*Scirpus* sp. seed
Hecla Island 97301-010 49-51 cm	CAMS-44529	1850 ± 50	*Scirpus* sp. seed
Grassy Narrows 97301-011 35-38 cm	CAMS-44530	370 ± 70	*Scirpus* sp. seed
Elk Island 97301-014 4-6 cm	CAMS-46194	1420 ± 60	*Bidens* sp. seeds
Elk Island 97301-014 48-50 cm	CAMS-44531	1800 ± 60	*Ranunculus sceleratus* L. seeds
Spider Is. 96-1	BGS-1906	390 ± 70	*Larix*
Spider Is. 96-2	BGS-1907	255 ± 75	*Larix*
Marchand Pt. 96-1	BGS-1908	2050 ± 80	*Larix*
Marchand Pt. 96-2	BGS-1909	1100 ± 75	*Larix*
Disbrowe Pt. 96-1	BGS-1910	130 ± 70	*Pinus*
Disbrowe Pt. 96-2	BGS-1911	260 ± 75	*Pinus*
Observation Pt. 96-1	BGS-1912	1795 ± 75	*Larix*
Observation Pt. 96-2	BGS-1913	1810 ± 80	*Larix*
Observation Pt. Man 93-1	BGS-1632	160 ± 70	*Larix*
Sans Souci NB-90-69-20(a)	BGS-1477	3600 ± 80	soil
Sans Souci NB-90-69-20(b)	BGS-1478	1200 ± 70	peat
West Channel NB-90-69-2(a)	BGS-1439	335 ± 65	*Salix*
West Channel NB-90-69-2(c)	BGS-1448	230 ± 70	wood
Pruden Bay NB-90-69-4(i)	BGS-1440	290 ± 70	*Salix*
Pruden Bay NB-90-69-4(p)	BGS-1449	modern	peat
Pruden Bay NB-90-69-4(w)	BGS-1450	210 ± 70	wood
Patricia Beach NB-90-69-5(a)	BGS-1442	190 ± 65	*Populus*
Patricia Beach NB-90-5	GSC-5269	modern	*Salix*
Beaconia Beach NB-90-69-8(a)	BGS-1443	260 ± 80	organic muck
Beaconia Beach NB-90-69-8(i)	BGS-1444	185 ± 65	*Salix*
Beaconia Beach NB-90-69-8(j)	BGS-1445	modern	wood
Beaconia Beach NB-90-8	GSC-5264	590 ± 50	*Larix*
Pruden Creek NB-90-69-9	BGS-1446	230 ± 70	wood
Stoney Point NB-90-69-19(b)	BGS-1451	modern	wood
Grand Beach 93-1 (40 cm)	BGS-1662	270 ± 70	fibrous peat
Mossy Point No. 1 (1.4 m)	BGS-1751	3460 ± 80	peat
Traverse Bay E.N.-1979-3	GSC-3281	840 ± 100	*Strophitus undulatus* shell
Netley Marsh NB-90-69-6(j)	BGS-1947	545 ± 80	*Lampsilis radiata siliquoidea* (Barnes) shells
Netley Marsh NB-90-2(c)	GSC-5258	modern	*Ulmus americana*
Willow Point 96305-030	BGS-1946	775 ± 105	*Lampsilis radiata siliquoidea* (Barnes) shells
Netley Marsh NB-96-1 3.1 m	CAMS-27256	650 ± 60	*Scirpus* cf *paludosus* seed

Netley Marsh NB-96-3 2.16 m	CAMS-27255	450 ± 70	*Scirpus* cf *acutus* seed
Willow Point WP96-1 1.8 m	CAMS-27257	750 ± 70	*Scirpus* cf *acutus* seed
Willow Point WP96-2 2.5 m	CAMS-27258	1100 ± 10	*Scirpus* cf *acutus* seed
Elk Island Lk. Winnipeg-1973-1 T	GSC-1980	1060 ± 210	peat
Elk Island Lk. Winnipeg-1973-1 B	GSC-1977	1660 ± 60	peat

Lab. Number: **BETA-81335**
Field Number: 94900 LW 122aGC 388.5-392 cm below water-sediment interface
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.29
Material: bulk sediment
Latitude: 50° 39.39' N
Longitude: 96° 48.29' W
Elevation: 217.8 m (lake level); 200.6 m (sample elevation)
Locality: approximately 30 km from southern shoreline, central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -16.1 ‰
Normalized Age: 11050 ± 270 yr BP
Significance: age of Lake Winnipeg sediments in South Basin (anomalous)
Assoc. Dates: CAMS-17434 4040 ± 70 yr BP; CAMS-34551 4000 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Stratigraphy: 4.77 m lake sediment and peat layer recovered within a 6 cm diameter by 9 m long gravity corer in 9.8 m water depth. Dated sediment is from weakly calcareous clay-silt mud (300-426.5 cm) approximately 35 cm above conformable contact (426.5 cm) underlain by peat (426.5-435 cm) and stiff clayey silt (435-472 cm). Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (top of stiff clayey silt); this core was significantly shortened in the coring process (Lewis et al., this volume).

Comments (A.M. Telka): Date of 11.1 ka on Lake Winnipeg sediments is anomalously old in comparison to the excellently preserved *Scirpus* seed date of 4.0 ka from peat within this core (see associated dates CAMS-17434 and CAMS-34551), demonstrating an apparent error, probably from the incorporation of carbon older than late Quaternary within Lake Winnipeg watershed.

Lab. Number: **BGS-1439**
Field Number: NB-90-69-2(a)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.06.25
Material: wood
Taxon Dated: *Salix*
Encl. Material: silty clay
Latitude: 50° 24' 10" N
Longitude: 96° 51' 55" W
Elevation: 217.2 m (lake level)
Locality: Red River Delta, south end of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 335 ± 65 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, rate of transgression
Assoc. Dates: BGS-1448 230 ± 70 yr BP
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Tree stumps rooted in silty clay on the foreshore.

Comments (E. Nielsen): Stumps are perpetually wet. This date helps to determine the rate of transgression of Lake Winnipeg. Trees originally grew in marsh but are now found about 17 m out in Lake Winnipeg.

Lab. Number: **BGS-1440**
Field Number: NB-90-69-4(I)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen

Collected: 1990.06.29
Material: wood
Taxon Dated: *Salix* sp.
Encl. Material: sand
Latitude: 50° 23' 25" N
Longitude: 96° 46' 25" W
Elevation: 217.3 m (lake level)
Locality: Red River Delta, south end of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 290 ± 70 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, rate of transgression
Assoc. Dates: BGS-1449 modern; BGS-1450 210 ± 70 yr BP
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Trees rooted in sand on the foreshore. Stumps underwater and perpetually wet.

Comments (E. Nielsen): Trees originally grew in marsh around lagoon on shore side of beach, subsequently transgressed by the beach and dune complex due to high water level. This date helps to determine the rate of transgression of Lake Winnipeg.

Lab. Number: **BGS-1442**
Field Number: NB-90-69-5(a)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.07.06
Material: wood
Taxon Dated: *Populus* sp.
Encl. Material: sand
Latitude: 50° 26' 10" N
Longitude: 96° 35' 20" W
Elevation: 217.4 m (lake level)
Locality: Patricia Beach, southeast shore of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 190 ± 65 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change and rate of transgression
Assoc. Dates:
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Wood collected on waters edge on the foreshore of Patricia Beach.

Comments (E. Nielsen): This date helps to determine the rate of transgression of Lake Winnipeg.

Lab. Number: **BGS-1443**
Field Number: NB-90-69-8(a)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.07.11
Material: organic muck
Taxon Dated:
Encl. Material: silty clay
Latitude: 50° 26' 50" N
Longitude: 96° 34' 35" W
Elevation: 217.4 m (lake level)

Locality: foreshore of Beaconia Beach, southeast shore of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 260 ± 80 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change and rate of transgression
Assoc. Dates: BGS-1444 185 ± 65 yr BP
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Collection site was underwater on the foreshore about 1 m from the water's edge and about 44 m from the lagoon.

Comments (E. Nielsen): This date helps to determine the rate of transgression of Lake Winnipeg.

Lab. Number: **BGS-1444**
Field Number: NB-90-69-8(i)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.07.11
Material: wood
Taxon Dated: *Salix*
Encl. Material: sand
Latitude: 50° 26' 30" N
Longitude: 96° 34' 50" W
Elevation: 217.4 m (lake level)
Locality: foreshore of Beaconia Beach, southeast shore of Lake Winnipeg, Manitoba
Uncorrected Age: 185 ± 65 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, rate of transgression
Assoc. Dates: BGS-1443 260 ± 80 yr BP
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Stump sticking out of the water 7.5 m from the shore. Water depth about 0.55 m. Distance to the lagoon about 50 m.

Comments (E. Nielsen): This date helps to determine the rate of transgression of Lake Winnipeg.

Lab. Number: **BGS-1445**
Field Number: NB-90-69-8(j)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.07.11
Material: wood
Taxon Dated:
Encl. Material:
Latitude: 50° 26' 30" N
Longitude: 96° 34' 50" W
Elevation: 217.4 m (lake level)
Locality: lagoon behind Beaconia Beach, southeast side of Lake Winnipeg, Manitoba
Uncorrected Age: modern
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, rate of transgression
Assoc. Dates:
References:

Stratigraphy: Tree sticking out of lagoon about 100 m from the nearest living trees. Water level in lagoon at about ground level where the tree is rooted.

Comments (E. Nielsen): This date helps to determine the rate of transgression of Lake Winnipeg.

Lab. Number: **BGS-1446**
Field Number: NB-90-69-9
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.07.13
Material: wood
Taxon Dated:
Encl. Material: sand
Latitude: 50° 23' 25" N
Longitude: 96° 45' 10" W
Elevation:
Locality: Pruden Creek, Manitoba
Uncorrected Age: 230 ± 70 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change and rate of transgression
Assoc. Dates:
References:

Stratigraphy: Driftwood washed up on beach. Heavy rusty stain on wood which is curled like an umbrella. Lots of old looking wood on this part of the shore.

Comments (E. Nielsen): This date indicates presence of submerged woodland in the offshore.

Lab. Number: **BGS-1448**
Field Number: NB-90-69-2(c)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.06.25
Material: wood
Taxon Dated:
Encl. Material: silty clay
Latitude: 50° 24' 10" N
Longitude: 96° 51' 55" W
Elevation: 217.2 m (lake level)
Locality: Red River Delta in the south end of Lake Winnipeg, Manitoba
Uncorrected Age: 230 ± 70 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change and rate of transgression
Assoc. Dates: BGS-1439 335 ± 65 yr BP
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Log rooted in silty clay on foreshore. Waterlogged and perpetually wet. Tree originally grew in marsh in the lagoon behind (i.e. south of the barrier).

Comments (E. Nielsen): This date helps to determine the rate of transgression of Lake Winnipeg.

Lab. Number: **BGS-1449**
Field Number: NB-90-69-4(p)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.08.09
Material: peat
Taxon Dated:
Encl. Material:
Latitude: 50° 23' 25" N
Longitude: 96° 46' 25" W
Elevation: 217.3 m (lake level)
Locality: Red River Delta, south end of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: modern
$\delta^{13}C$:
Normalized Age:
Significance: lake level change and rate of transgression
Assoc. Dates: BGS-1440 290 ± 70 yr BP; BGS-1450 210 ± 70 yr BP
References:

Stratigraphy: Peat outcropping on foreshore, was originally deposited in lagoon behind barrier.

Comments (E. Nielsen): Peat enclosing log sample NB-90-69-4(w) tests relative ages of peat and wood.

Lab. Number: **BGS-1450**
Field Number: NB-90-69-4(w)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.08.09
Material: wood
Taxon Dated:
Encl. Material: peat
Latitude: 50° 23' 25" N
Longitude: 96° 46' 25" W
Elevation: 217.3 m (lake level)
Locality: Red River Delta, south end of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 210 ± 70 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change and rate of transgression
Assoc. Dates: BGS-1440 290 ± 70 yr BP; BGS-1449 modern
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Stump was rooted in peat on foreshore. Stump was underwater most of the time. The tree originally grew in marsh behind barrier island.

Comments (E. Nielsen): This date helps to estimate the rate of transgression of Lake Winnipeg.

Lab. Number: **BGS-1451**
Field Number: NB-90-69-19(b)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.08.01
Material: wood
Taxon Dated:

Encl. Material: gravel
Latitude: 50° 25' 30" N
Longitude: 96° 37' 45" W
Elevation: ~218.8 m
Locality: Stoney Point, near Patricia Beach at the southeastern end of Lake Winnipeg, Manitoba
Uncorrected Age: modern
$\delta^{13}C$:
Normalized Age:
Significance: geomorphic processes, storm surge
Assoc. Dates:
References:

Stratigraphy: High gravel beach about 1.5 m above present level of Lake Winnipeg. Wood sticking out of gravel on the surface.

Comments (E. Nielsen): Wood was deposited during higher level of Lake Winnipeg, possibly a storm surge, and is modern.

Lab. Number: **BGS-1477**
Field Number: NB-90-69-20(a)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.10.10
Material: soil
Encl. Material: clay
Latitude: 50° 25' 30" N
Longitude: 96° 56' 25" W
Elevation: 216.9 m (lake level)
Locality: Sans Souci Beach, southwest shore of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 3600 ± 80 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, rate of transgression, and Agassiz Unconformity
Assoc. Dates: BGS-1478 1200 ± 70 yr BP
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Collection site was on the foreshore of Lake Winnipeg, exposed at low water level.

Comments (E. Nielsen): Dated soil is from infilled desiccation cracks of polygons 16 to 30 cm in diameter, from top of Lake Agassiz sediment, directly below Agassiz Unconformity. Desiccation cracks are believed to have formed during periods of drought and were subsequently infilled by wind blown topsoil. Date also provides a maximum age for Lake Winnipeg transgression.

Lab. Number: **BGS-1478**
Field Number: NB-90-69-20(b)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.10.10
Material: peat
Taxon Dated:
Encl. Material: clay
Latitude: 50° 25' 30" N
Longitude: 96° 56' 25" W
Elevation: 216.9 m (lake level)
Locality: Sans Souci Beach, southwest shore of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 1200 ± 70 yr BP
$\delta^{13}C$:

Normalized Age:
Significance: lake level change, age estimate for the transgression of Lake Winnipeg
Assoc. Dates: BGS-1477 3600 ± 80 yr BP
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Foreshore of Lake Winnipeg exposed during low water level. Sample was from the surface which is usually underwater. Peat is stratigraphically above the Lake Agassiz clay, and forms part of a Holocene marsh sequence being eroded by Lake Winnipeg. Shore is slowly eroding.

Comments (E. Nielsen): This date provides information on the rate of southward transgression of Lake Winnipeg.

Lab. Number: **BGS-1632**
Field Number: Man 93-1
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1993.05.24
Material: wood (log and stump)
Taxon Dated: *Larix* sp. identified by E. Nielsen
Encl. Material: calcareous sand
Latitude: 51° 04' 30" N
Longitude: 96° 26' 25" W
Elevation: 217.4 m (lake level)
Locality: north side of Observation Point, southeast shore of Lake Winnipeg, Manitoba
Uncorrected Age: 160 ± 70 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change, transgression, climate change, low-water phase
Assoc. Dates:
References: Nielsen, 1998; Nielsen & Conley, 1994

Stratigraphy: Surface collection of wood from the upper foreshore.

Comments (E. Nielsen): This date helps to determine the rate of transgression in the southern basin of Lake Winnipeg, and possibly dates a climate-induced low-water phase of Lake Winnipeg.

Lab. Number: **BGS-1662**
Field Number: Grand Beach 93-1 (40 cm)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1993.09.01
Material: fibrous peat
Taxon Dated:
Encl. Material:
Latitude: 50° 33' 40" N
Longitude: 96° 36' 50" W
Elevation: 218.5 m
Locality: Grand Beach, Lake Winnipeg, Manitoba
Uncorrected Age: 270 ± 70 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change and rate of transgression
Assoc. Dates:
References:

Stratigraphy: Thin unit of peat overlying at least 50 cm and underlying 40 cm calcareous dune sand. Collection site is from the lagoon side of the barrier beach at Grand Beach

Comments (E. Nielsen): The sample dates a higher than present level of Lake Winnipeg.

Lab. Number: **BGS-1751**
Field Number: Mossy Point No. 1 (1.4 m)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1994.08.22
Material: basal peat
Taxon Dated:
Encl. Material:
Latitude: 53° 42' N
Longitude: 97° 55' W
Elevation: ~220 m
Locality: shore cliff section 1 km south of Warren Landing, North Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 3460 ± 80 yr BP
δ^{13}C:
Normalized Age:
Significance: peat initiation
Assoc. Dates:
References:

Stratigraphy: Basal material from >1 m peat overlying Lake Agassiz clay in cliff section exposed along north shore of Lake Winnipeg.

Comments (E. Nielsen): The sample dates the initiation of peat accumulation in the area.

Lab. Number: **BGS-1906**
Field Number: Spider Is. 96-1
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.08.25
Material: wood from rooted tree stump
Taxon Dated: *Larix* sp. identified by E. Nielsen
Encl. Material: sand
Latitude: 53° 30' N
Longitude: 97° 43' W
Elevation: 217.7 m (lake level)
Locality: Spider Islands, northeast shore of North Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 390 ± 70 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change, submergence
Assoc. Dates: BGS-1907 255 ± 75 yr BP
References: Nielsen, E., this volume

Stratigraphy: Submerged rooted tree stump on the foreshore of the present beach. Root crown, on the day of collection, at about the same elevation as the water level in Lake Winnipeg.

Comments (E. Nielsen): This date helps to determine the rate of water-level rise in Lake Winnipeg

Lab. Number: **BGS-1907**

Field Number: Spider Is. 96-2
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.08.25
Material: wood from rooted tree stump
Taxon Dated: *Larix* identified by E. Nielsen
Encl. Material: sand
Latitude: 53° 30' N
Longitude: 97° 43' W
Elevation: 217.7 m (lake level)
Locality: Spider Islands, northeast shore of North Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 255 ± 75 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, submergence
Assoc. Dates: BGS-1906 390 ± 70 yr BP
References: Nielsen, E., this volume

Stratigraphy: Submerged rooted tree stump on the foreshore of the present beach. Root crown, on the day of collection, at about the same elevation as the water level in Lake Winnipeg.

Comments (E. Nielsen): This date helps to determine the rate of water-level rise in Lake Winnipeg

Lab. Number: **BGS-1908**
Field Number: Marchand Pt. 96-1
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.08.26
Material: wood from rooted tree stump
Taxon Dated: *Larix* sp. identified by E. Nielsen
Encl. Material: sand
Latitude: 52° 49' N
Longitude: 97° 22' W
Elevation: 217.7 m (lake level); 217.2 m (sample elevation)
Locality: south of Marchand Point, eastern shore of North Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 2050 ± 80 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, submergence (anomalous)
Assoc. Dates: BGS-1909 1100 ± 75 yr BP
References: Nielsen, E., this volume

Stratigraphy: Submerged rooted tree stump on the foreshore of the present beach. Root crown, on day of collection, 0.50 m below the level of Lake Winnipeg.

Comments (E. Nielsen & D.L. Forbes): This date was intended to help determine the rate of water-level rise in the northern basin of Lake Winnipeg, but is anomalously old, indicating that the sampled stump is buried in an old fen which is now being exhumed by Lake Winnipeg shoreline erosion.

Lab. Number: **BGS-1909**
Field Number: Marchand Pt. 96-2
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.08.26

Material: wood from rooted tree stump
Taxon Dated: *Larix* sp. identified by E. Nielsen
Encl. Material: sand
Latitude: 52° 49' N
Longitude: 97° 22' W
Elevation: 217.7 m (lake level); 217.2 m (sample elevation)
Locality: south of Marchand Point, eastern shore of North Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 1100 ± 75 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change and shoreline submergence (anomalous)
Assoc. Dates: BGS-1908 2050 ± 80 yr BP
References: Nielsen, E., this volume

Stratigraphy: Submerged rooted tree stump on the foreshore of the present beach. Root crown, on day of collection, 0.50 m below the level of Lake Winnipeg.

Comments (E. Nielsen & D.L. Forbes): This date was intended to help determine the rate of water-level rise in the northern basin of Lake Winnipeg, but is anomalously old, indicating that the sampled stump is buried in an old fen which is now being exhumed by Lake Winnipeg shoreline erosion.

Lab. Number: **BGS-1910**
Field Number: Disbrowe Pt. 96-1
Submitter(s): E. Nielsen
Collector(s): E. Nielsen, D.L. Forbes
Collected: 1996.08.17
Material: wood
Taxon Dated: *Pinus* sp. identified by E. Nielsen
Encl. Material: sand
Latitude: 52° 25' N
Longitude: 97° 08' W
Elevation: ~219 m
Locality: Disbrowe Point, north of Berens River, North Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 130 ± 70 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change, geomorphic processes, spit development
Assoc. Dates: BGS-1911 260 ± 75 yr BP; CAMS-44526 modern
CAMS-44527 2510 ± 50 yr BP; CAMS-44528 2910 ± 50 yr BP
References: Nielsen, E., this volume; Forbes, D.L., this volume

Stratigraphy: Freshly exposed dune ridge with buried line of logs approximately 2 m above present lake level.

Comments (E. Nielsen & D.L. Forbes): This date gives a minimum age for the spit at Disbrowe Point and dates the washover that planed off the dune ridge. Although the point did not originate as a spit (Forbes, 2000), it now functions as such. Dated section is near the narrowest part about halfway along the spit.

Lab. Number: **BGS-1911**
Field Number: Disbrowe Pt. 96-2
Submitter(s): E. Nielsen
Collector(s): E. Nielsen, D.L. Forbes
Collected: 1996.08.17
Material: wood
Taxon Dated: *Pinus* sp. identified by E. Nielsen

Encl. Material: sand
Latitude: 52° 25' N
Longitude: 97° 08' W
Elevation: ~219 m
Locality: Disbrowe Point, north of Berens River, North Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 260 ± 75 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change, geomorphic processes, spit development
Assoc. Dates: BGS-1910 130 ± 70 yr BP; CAMS-44526 modern;
CAMS-44527 2510 ± 50 yr BP; CAMS-44528 2910 ± 50 yr BP
References: Nielsen, E., this volume; Forbes, D.L., this volume

Stratigraphy: Freshly exposed dune ridge with buried line of logs approximately 2 m above present day lake level.

Comments (E. Nielsen & D.L. Forbes): This date gives a minimum age for the spit at Disbrowe Point and dates the washover that planed off the dune ridge. See BGS-1910.

Lab. Number: **BGS-1912**
Field Number: Observation Pt. 96-1
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.08.14
Material: wood from rooted tree stump
Taxon Dated: *Larix* sp. identified by E. Nielsen
Encl. Material: sand
Latitude: 51° 04' N
Longitude: 96° 26' W
Elevation: 217.7 m (lake level); 217.5 m (sample elevation)
Locality: Observation Point, northeast shore of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 1795 ± 75 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change and shoreline submergence (anomalous)
Assoc. Dates: BGS-1913 1810 ± 80 yr BP; BGS-1632 160 ± 70 yr BP
References: Nielsen, E., this volume

Stratigraphy: Submerged rooted tree stump on the foreshore of the present beach. Root crown, on day of collection, approximately 20 cm below the level of Lake Winnipeg.

Comments (E. Nielsen): This sample was intended to help determine rate of water-level rise in the northern south basin of Lake Winnipeg. The date is anomalously old when compared to BGS-1632 (160 ± 70 yr BP). This log (96-1) and 96-2 are from the south side of Observation Point and are believed to be logs buried in an old fen which is now being exhumed by Lake Winnipeg shoreline erosion.

Lab. Number: **BGS-1913**
Field Number: Observation Pt. 96-2
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.08.14
Material: wood from rooted tree stump
Taxon Dated: *Larix* sp. identified by E. Nielsen
Encl. Material: sand
Latitude: 51° 04' N
Longitude: 96° 26' W

Elevation: 217.5 m (lake level)
Locality: Observation Point, northeast shore of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 1810 ± 80 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change and shoreline submergence (anomalous)
Assoc. Dates: BGS-1912 1795 ± 75 yr BP; BGS-1632 160 ± 70 yr BP
References: Nielsen, E., this volume

Stratigraphy: Submerged rooted tree stump on the foreshore of the present beach. Root crown, on day of collection, approximately 20 cm below the level of Lake Winnipeg.

Comments (E. Nielsen): This sample was intended to help determine the rate of water-level rise in the northern south basin of Lake Winnipeg. The date is anomalously old when compared to BGS-1632 (160 ± 70 yr BP). This log (96-2) and 96-1 are from the south side of Observation Point and are believed to be logs buried in an old fen which is now being exhumed by Lake Winnipeg shoreline erosion.

Lab. Number: **BGS-1946**
Field Number: 96305-030 (20 cm)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen, D.L. Forbes
Collected: 1996.08.10
Material: freshwater shells
Taxon Dated: *Lampsilis radiata siliquoidea* (Barnes) identified by E. Nielsen
Encl. Material: calcareous sand
Latitude: 50° 35' 20" N
Longitude: 96° 57' 10" W
Elevation: ~219.1 m
Locality: south side of Willow Point, south of Gimli, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 775 ± 105 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change, age estimate for beach ridge
Assoc. Dates: GSC-3281 840 ± 100; BGS-1947 545 ± 80
References: Forbes, D.L., this volume

Stratigraphy: Approximately 1.5 m thick beach sand from an eroding beach about 1 m above present lake level. Dated shells are from near the top ~20 cm of beach sand.

Comments (E. Nielsen & D.L. Forbes): The shells are thought to date the formation of a high berm on the south side of Willow Point. The 'hard-water' error (which may vary between species) is estimated to be between 500 and 840 years in this area, based on the dating of a pre-bomb modern sample of *Strophitus undulatus* (Say) collected at mouth of Winnipeg River in 1941 (GSC-3281) and dated samples of various mollusc species and terrestrial organics at corresponding levels in cores (cf. CAMS-35501, CAMS-35496, and CAMS-35615 from core 96900-224; CAMS-35495 and CAMS-32193 from core 96900-220; CAMS-38680 and CAMS-35616 from core 96900-221). This sample may therefore be modern or (after adjustment for unknown isotopic fractionation) up to 200-500 years old.

Lab. Number: **BGS-1947**
Field Number: NB-90-69-6(j)
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1990.07.09
Material: freshwater shells
Taxon Dated: *Lampsilis radiata siliquoidea* (Barnes) identified by E. Nielsen
Encl. Material: calcareous sand
Latitude: 50° 24.5' N

Longitude: 96° 54.0' W
Elevation: ~220.6 m
Locality: approximately 1 km west of the mouth of Salamonia Channel, south shore of South Basin, Lake Winnipeg, Manitoba
Uncorrected Age: 545 ± 80 yr BP
$\delta^{13}C$:
Normalized Age:
Significance: lake level change
Assoc. Dates: GSC-3281 840 ± 100; BGS-1946 775 ± 105 yr BP
References: Forbes, D.L. et al., this volume

Stratigraphy: Eroding beach freshly exposed. Dated shells are from near the top of a 2 m high beach ridge.

Comments (E. Nielsen): This sample dates a high-water stand of Lake Winnipeg or possibly a storm surge in 1966. If a 'hard-water' correction is applied to this date then the sample is probably modern (cf. BGS-1946).

Lab. Number: **CAMS-17434**
Field Number: 94900 LW 122aGC 425-433 cm below water-sediment interface
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.29
Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by R.E. Vance
Encl. Material: peat
Latitude: 50° 39.39' N
Longitude: 96° 48.29' W
Elevation: 217.8 m (lake level); 200.2 m (sample elevation)
Locality: approximately 30 km from southern shoreline, central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 4040 ± 70 yr BP
Significance: dates marsh sedimentation in South Basin, Lake Winnipeg
Assoc. Dates: CAMS-34551 4000 ± 60 yr BP; CAMS-46186 4030 ± 50 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Analyst: R.E. Vance

Stratigraphy: 4.77 m lake sediment and peat recovered in a 6 cm diameter by 9 m long gravity corer in 9.8 m water depth. Dated bulrush (*Scirpus* sp.) seed is from peat unit of two beds of clayey silt and peat (426.5-435 cm) overlying stiff Lake Agassiz clayey silt and underlying conformable contact with Lake Winnipeg clay-silt mud. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (top of stiff clayey silt); this core was significantly shortened in the coring process (Lewis et al., this volume).

Comments (R.E. Vance): Peat layer is the only organic-rich layer observed in the 94900 core series. Plant macrofossil assemblage is rich and varied including rush (*Juncus* sp.), sedge (*Carex* spp.), bulrush (*Scirpus* sp.), skunkweed (*Chara* sp.), horned pondweed (*Zannichellia palustris* L.), cat-tail (*Typha* sp.), goosefoot (*Chenopodium* sp.) and samphire (*Salicornia rubra* A. Nels.). Preservational state of the dated bulrush seed is excellent with basal bristles still attached and displaying a well shaped pristine style tip. Plant macrofossil evidence suggests that the core site was situated near shoreline at 4.0 ka.

Lab. Number: **CAMS-19445**
Field Number: 94900 LW 122aGC 17-23 cm below water-sediment interface
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.29
Material: bulk sediment
Latitude: 50° 39.39' N

Longitude: 96° 48.29' W
Elevation: 217.8 m (lake level); 204.3 m (sample elevation)
Locality: approximately 30 km from southern shoreline, central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -27.7 ‰
Normalized Age: 3990 ± 50 yr BP
Significance: age of Lake Winnipeg sediments (anomalous)
Assoc. Dates: CAMS-17434 4040 ± 70 yr BP; CAMS-34551 4000 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Stratigraphy: 4.77 m lake sediment and peat recovered with a 6 cm diameter by 9 m long gravity corer in 9.8 m water depth. Dated sediment is from near the top of noncalcareous clay-silt mud (0-300 cm) approximately 403 cm above conformable contact (426.5 cm) underlain by peat (426.5-435 cm) and stiff clayey silt (435-472 cm). Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (top of stiff clayey silt); this core was significantly shortened in the coring process (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): This age of 4.0 ka on near-surface Lake Winnipeg sediments is anomalously old in comparison to excellently preserved *Scirpus* seed dates of 4.0 ka from deeper peat within this core (CAMS-17434 & CAMS-34551), probably resulting from the incorporation of carbon older than late Quaternary within the Lake Winnipeg watershed. This age determination should be ignored.

Lab. Number: **CAMS-19446**
Field Number: 94900 LW 122aGC 118-123 cm below water-sediment interface
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.29
Material: bulk sediment
Latitude: 50° 39.39' N
Longitude: 96° 48.29' W
Elevation: 217.8 m (lake level); 203.3 m (sample elevation)
Locality: approximately 30 km from southern shoreline, central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -27.9 ‰
Normalized Age: 5820 ± 50 yr BP
Significance: age of Lake Winnipeg sediments (anomalous)
Assoc. Dates: CAMS-17434 4040 ± 70 yr BP; CAMS-34551 4000 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Stratigraphy: 4.77 m lake sediment and peat recovered with a 6 cm diameter by 9 m long gravity corer in 9.8 m water depth. Dated sediment is from within noncalcareous clay-silt mud (0-300 cm) approximately 303 cm above conformable contact (426.5 cm) underlain by peat (426.5-435 cm) and stiff clayey silt (435-472 cm). Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (top of stiff clayey silt); this core was significantly shortened in the coring process (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Date of 5.8 ka on Lake Winnipeg sediments is anomalously old in comparison to the excellently preserved *Scirpus* seed dates of 4.0 ka from deeper peat within this core (CAMS-17434 & CAMS-34551), probably resulting from the incorporation of carbon older than late Quaternary within the Lake Winnipeg watershed. This age determination should be ignored.

Lab. Number: **CAMS-19447**
Field Number: 94900 LW 122aGC 188-192 cm below water-sediment interface
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.29
Material: bulk sediment
Latitude: 50° 39.39' N
Longitude: 96° 48.29' W
Elevation: 217.8 m (lake level); 202.6 m (sample elevation)

Locality: approximately 30 km from southern shoreline, central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -27.7 ‰
Normalized Age: 6900 ± 60 yr BP
Significance: age of Lake Winnipeg sediments (anomalous)
Assoc. Dates: CAMS-17434 4040 ± 70 yr BP; CAMS-34551 4000 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Stratigraphy: 4.77 m lake sediment and peat recovered with a 6 cm diameter by 9 m long gravity corer in 9.8 m water depth. Dated sediment is from within noncalcareous clay-silt mud (0-300 cm) approximately 234 cm above conformable contact (426.5 cm) underlain by peat (426.5-435 cm) and stiff clayey silt (435-472 cm). Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (top of stiff clayey silt); this core was significantly shortened in the coring process (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Date of 6.9 ka on Lake Winnipeg sediments is anomalously old in comparison to the excellently preserved *Scirpus* seed dates of 4.0 ka from deeper peat within this core (CAMS-17434 & CAMS-34551), probably resulting from the incorporation of carbon older than late Quaternary within the Lake Winnipeg watershed. This age determination should be ignored.

Lab. Number: **CAMS-19448**
Field Number: 94900 LW 122aGC 268.5-272 cm below water-sediment interface
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.29
Material: bulk sediment
Latitude: 50° 39.39' N
Longitude: 96° 48.29' W
Elevation: 217.8 m (lake level); 201.8 m (sample elevation)
Locality: approximately 30 km from southern shoreline, central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -27.5 ‰
Normalized Age: 7570 ± 50 yr BP
Significance: age of Lake Winnipeg sediments (anomalous)
Assoc. Dates: CAMS-17434 4040 ± 70 yr BP; CAMS-34551 4000 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Stratigraphy: 4.77 m lake sediment and peat recovered with a 6 cm diameter by 9 m long gravity corer in 9.8 m water depth. Dated sediment is from near the base of noncalcareous clay-silt mud (0-300 cm) approximately 154 cm above conformable contact (426.5 cm) underlain by peat (426.5-435 cm) and stiff clayey silt (435-472 cm). Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (top of stiff clayey silt); this core was significantly shortened in the coring process (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Date of 7.6 ka on Lake Winnipeg sediments is anomalously old in comparison to the excellently preserved *Scirpus* seed dates of 4.0 ka from deeper peat within this core (CAMS-17434 & CAMS-34551), probably resulting from the incorporation of carbon older than late Quaternary within the Lake Winnipeg watershed.

Lab. Number: **CAMS-19449**
Field Number: 94900 LW 122aGC 318.5-322 cm below water-sediment interface
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.29
Material: bulk sediment
Latitude: 50° 39.39' N
Longitude: 96° 48.29' W
Elevation: 217.8 m (lake level); 201.3 m (sample elevation)
Locality: Approximately 30 km from southern shoreline, central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:

$\delta^{13}C$: -28.4 ‰
Normalized Age: 7560 ± 70 yr BP
Significance: age of Lake Winnipeg sediments (anomalous)
Assoc. Dates: CAMS-17434 4040 ± 70 yr BP; CAMS-34551 4000 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Stratigraphy: 4.77 m lake sediment and peat recovered with a 6 cm diameter by 9 m long gravity corer in 9.8 m water depth. Dated sediment is from near the top of weakly calcareous clay-silt mud (300-426.5 cm) approximately 104 cm above conformable contact (426.5 cm) underlain by peat (426.5-435 cm) and stiff clayey silt (435-472 cm). Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (top of stiff clayey silt); this core was significantly shortened in the coring process (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Date of 7.6 ka on Lake Winnipeg sediments is anomalously old in comparison to the excellently preserved *Scirpus* seed dates of 4.0 ka from deeper peat within this core (CAMS-17434 & CAMS-34551), probably resulting from the incorporation of carbon older than late Quaternary within the Lake Winnipeg watershed.

Lab. Number: **CAMS-27255**
Field Number: NB-96-3 2.16 m
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.03.13
Material: 3 great bulrush seeds
Taxon Dated: *Scirpus* cf *acutus* identified by R.E. Vance
Encl. Material: organic silt
Latitude: 50° 18.22' N
Longitude: 96° 52.57' W
Elevation: ~217.4 m (lake level); 215.2 m (sample elevation)
Locality: Netley Lake, Netley Marsh, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 450 ± 70 yr BP
Significance: basal age for Netley Marsh sediments
Assoc. Dates: CAMS-27256 650 ± 60 yr BP
References:
Analyst: R.E. Vance

Stratigraphy: Auger sample obtained in 1.0 m of water. Dated bulrush seeds are from the base of organic silt (0-114 cm) overlying Lake Agassiz clay.

Comments (A.M. Telka & R.E. Vance): Preservational state of the dated bulrush seeds is excellent with bristles and distal tips attached. Date of 0.45 ka provides a minimum age for the beginning of Netley Marsh sedimentation.

Lab. Number: **CAMS-27256**
Field Number: NB-96-1 3.1 m
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.03.13
Material: prairie bulrush seed
Taxon Dated: *Scirpus* cf *paludosus* identified by R.E. Vance
Encl. Material: organic rich clay
Latitude: 50° 18.98' N
Longitude: 96° 51.62' W
Elevation: ~217.4 m (lake level); 214.2 m (sample elevation)
Locality: Netley Lake, Netley Marsh, Manitoba
Uncorrected Age:

δ^{13}C: -25 ‰
Normalized Age: 650 ± 60 yr BP
Significance: basal age for Netley Marsh sediments
Assoc. Dates: CAMS-27255 450 ± 70 yr BP
References:
Analyst: R.E. Vance
Stratigraphy: Auger sample obtained in 1.3 m of water. Dated bulrush seed is from the base of firm brown organic-rich clay (0-190 cm) overlying Lake Agassiz clay.

Comments (A.M. Telka & R.E. Vance): Preservational state of the dated bulrush seed is excellent with bristles and distal tip attached. Date of 0.65 ka provides a minimum age estimate for the beginning of Netley Marsh sedimentation.

Lab. Number: **CAMS-27257**
Field Number: WP-96-1 1.80 m
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.03.14
Material: 3 great bulrush seeds
Taxon Dated: *Scirpus* cf *acutus* identified by R.E. Vance
Encl. Material:
Latitude: 50° 35.80' N
Longitude: 96° 57.88' W
Elevation: ~217.6 m (lake level); 215.8 m (sample elevation)
Locality: Willow Point, Manitoba
Uncorrected Age:
δ^{13}C: -25 ‰
Normalized Age: 750 ± 70 yr BP
Significance: age estimate for lagoon
Assoc. Dates: CAMS-27258 1100 ± 100 yr BP
References:
Analyst: R.E. Vance

Stratigraphy: Auger sample obtained in 1.5 m of water. Dated bulrush seeds are from the base of peaty brown clay (0-35 cm) overlying stiff Lake Agassiz clay.

Comments (A.M. Telka & R.E. Vance): Preservational state of the dated bulrush seeds is excellent with bristles and distal tips attached. Date of 0.75 ka provides a minimum age for the initiation of sedimentation in lagoon behind Willow Point.

Lab. Number: **CAMS-27258**
Field Number: WP-96-2 2.50 m
Submitter(s): E. Nielsen
Collector(s): E. Nielsen
Collected: 1996.03.14
Material: 3 great bulrush seeds
Taxon Dated: *Scirpus* cf *acutus* identified by R.E. Vance
Encl. Material:
Latitude: 50° 35.62' N
Longitude: 96° 57.50' W
Elevation: ~217.6 m (lake level); 215.1 m (sample elevation)
Locality: Willow Point, Manitoba
Uncorrected Age:
δ^{13}C: -25 ‰
Normalized Age: 1100 ± 100 yr BP
Significance: age estimate for lagoon

Assoc. Dates:	CAMS-27257 750 ± 70 yr BP
References:	
Analyst:	R.E. Vance

Stratigraphy: Auger sample obtained in 1.5 m of water. Dated bulrush seeds are from the base of peaty organic-rich clay and silt (0-105 cm) overlying firm Lake Agassiz clay.

Comments (A.M. Telka & R.E. Vance): Preservational state of the dated bulrush seeds is excellent with bristles and distal tips attached. Date of 1.1 ka provides a minimum basal age for the initiation of sedimentation in lagoon behind Willow Point.

Lab. Number:	**CAMS-32189**
Field Number:	94900 LW 104aGC 237-243 cm below water-sediment interface
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1994.08.23
Material:	two twigs
Taxon Dated:	unidentifiable
Encl. Material:	clay-silt mud and silty fine sand
Latitude:	53° 35.05' N
Longitude:	98° 05.11' W
Elevation:	217.5 m (lake level); 199.8 m (sample elevation)
Locality:	approximately 20 km from Warren Landing, northeast North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	7700 ± 50 yr BP
Significance:	age of Lake Winnipeg basal sediments in North Basin
Assoc. Dates:	
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 96-18
Analyst:	A.M. Telka

Stratigraphy: 3.65 m of Lake Winnipeg sediment recovered with a 10 cm diameter by 9 m long gravity corer in 16.2 m water depth. Dated twigs are from 7 to 13 cm below the base of clay silt mud in a basal 135 cm thick unit of interlaminated clay-silt mud and silty fine sand. Sample elevation is based on acoustic profile and seismic reflection travel time to the base of the mud (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Preservation of the two barkless twig fragments is fair, suggesting these twigs have been redeposited. The 7.7 ka age is the oldest date obtained on Lake Winnipeg sediments. The interpreted macrofossil assemblage typifies a marsh environment of mostly cat-tail (*Typha* sp.) with predominantly shoreline insect taxa of marsh (Helodidae) beetles, suggesting that the shoreline was close to the core site at the time of deposition. The lack of plant macrofossils of tree species within this sample further supports the interpretation that the dated twigs may be reworked.

Lab. Number:	**CAMS-32190**
Field Number:	94900 LW 115GC 256-263 cm below water-sediment interface
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1994.08.26
Material:	twig
Taxon Dated:	unidentifiable
Encl. Material:	silt-clay mud
Latitude:	50° 56.76' N
Longitude:	96° 40.90' W
Elevation:	217.8 m (lake level); 202.4 m (sample elevation)
Locality:	Pearson Reef, approximately 5 km off Hecla Island, South Basin, Lake Winnipeg
Uncorrected Age:	

$\delta^{13}C$: -25 ‰
Normalized Age: 3060 ± 70 yr BP
Significance: age estimate for base of mud overlying former beach and shoreface at Pearson Reef
Assoc. Dates:
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 96-23
Analyst: A.M. Telka

Stratigraphy: 2.76 m lake sediment recovered with a 6 cm diameter by 9 m long gravity corer in 10.7 m water depth. Dated twig is from basal Lake Winnipeg silt-clay mud with bioturbated? fine sand lenses , 5 to 12 cm above the contact with underlying fine and medium sand. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of sand (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Preservation of the twig is good with bark intact, indicating minimal transport prior to final deposition. Wood and twigs in various states of preservation are abundant in this sample. Plant macrofossils are represented by a few sedges (*Carex* spp.) and goosefoot (*Chenopodium* sp.) seeds. Insect remains are relatively abundant with both terrestrial and aquatic components. Shoreline type insects such as shore bugs (*Saldula* sp.) and marsh beetles (Helodidae) dominate the assemblage. An age of 3.1 ka is suggested for the paleobeach at Pearson Reef.

Lab. Number: **CAMS-32191**
Field Number: 94900 LW 106PC 176-182 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis, C.G. Rodrigues
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.23
Material: ostracodes
Taxon Dated: *Candona rawsoni* Tressler and *Candona subtriangulata* Benson and MacDonald identified by C.G. Rodrigues
Encl. Material: moderately calcareous clay-silt mud
Latitude: 53° 34.70' N
Longitude: 98° 05.83' W
Elevation: 217.6 m (lake level); 198.9 m (sample elevation)
Locality: approximately 20 km from Warren Landing, northeast North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -7 ‰
Normalized Age: 6910 ± 200 yr BP
Significance: age estimate for the basal coarse facies of Lake Winnipeg sediment
Assoc. Dates: CAMS-38675 6900 ± 80 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:
Analyst: C.G. Rodrigues

Stratigraphy: 7.89 m lake sediment (182 cm of Lake Winnipeg mud over 607 cm of Lake Agassiz sediments) recovered with a 10 cm diameter by 9 m long piston corer in 16.8 m water depth. Dated ostracodes are from 0 to 6 cm above the Agassiz Unconformity in a 23 cm thick unit of soft, moderately calcareous, clay-silt mud with silt and sand, directly overlying erosional contact with the underlying firm silty clay rhythmites deposited in Lake Agassiz. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (C.F.M. Lewis): This sample suffered a loss of gas during radiocarbon analysis; hence the relatively large error estimate. Date of 6.9 ka provides an age estimate for the basal coarse facies of Lake Winnipeg sediment. This age determination on biogenic carbonate is not corrected for 'hard-water' error and could therefore be several hundred years too old.

Lab. Number: **CAMS-32192**
Field Number: 96900 LW 202PC 174-179 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis, C.G. Rodrigues
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.23

Material: ostracodes
Taxon Dated: *Candona rawsoni* Tressler and *Candona subtriangulata* Benson and MacDonald identified by C.G. Rodrigues
Encl. Material: calcareous clayey silt mud
Latitude: 53° 43.2' N
Longitude: 98° 36.2' W
Elevation: 217.8 m (lake level); 203.4 m (sample elevation)
Locality: approximately 16 km from northern shoreline, North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -7 ‰
Normalized Age: 6810 ± 60 yr BP
Significance: age estimate for burial of Agassiz Unconformity by basal Lake Winnipeg sediment at most northerly site
Assoc. Dates:
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-01
Analyst: A.M. Telka

Stratigraphy: 5.79 m lake sediment recovered with a 10 cm diameter by 9 m long piston corer in 13.6 m water depth. Dated ostracodes lie at the base of a basal Lake Winnipeg clayey silt mud unit (116-179 cm), immediately over the Agassiz Unconformity, underlain by soft to firm, laminated, calcareous Lake Agassiz clay (179-341 cm).Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): This site is the most northerly one dated in the Lake Winnipeg series and provides an age estimate of 6.8 ka for the beginning of Lake Winnipeg sedimentation over the Agassiz Unconformity. The date may be anomalously old (by several hundred years) due to undetermined 'hard-water' error. Insect fossils within this sample are minimally represented by both aquatic and shoreline types. Plant macrofossils are non-existent except for a few charred fragments of wood. The lack of shoreline indicators from the combined fossil evidence suggests shoreline at 6.8 ka was probably not significantly nearer the core site than it is today.

Lab. Number: **CAMS-32193**
Field Number: 96900 LW 220PC 542-547 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.29
Material: shell
Taxon Dated: unidentified pelecypod valve, selected by C.G. Rodrigues
Encl. Material: calcareous sand
Latitude: 50° 56.8' N
Longitude: 96° 40.9' W
Elevation: 217.8 m (lake level); 201.5 m (sample elevation)
Locality: Pearson Reef, approximately 5 km off Hecla Island, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -7 ‰
Normalized Age: 4760 ± 70 yr BP
Significance: age of paleo-shoreface or lower beach at Pearson Reef
Assoc. Dates: CAMS-35495 3920 ± 70 yr BP; CAMS-35494 1970 ± 170 yr BP; CAMS-35500 2940 ± 80 yr BP; CAMS-46193 3870 ± 140 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Forbes, D.L. et al., this volume; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Stratigraphy: 5.53 m Lake Winnipeg sediment (4.07 m clay and silty clay mud with occasional sand interbeds over 1.46 m sand and gravel) recovered with a 10 cm diameter by 9 m long piston corer in 10.5 m water depth. Dated shell is from near base of core in fine calcareous sand with granules and occasional medium sand and pebbly gravel. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of sand (Lewis et al., this volume).

Comments (C.F.M. Lewis & D.L. Forbes): This dated mollusc and associated dates indicate that an aqueous environment existed at this site several hundred years before deposition of the former beach at Pearson Reef. This beach, at approximately 14 m below present mean lake level, developed *circa* 4 ka, after which it was abandoned by rising lake levels and buried by deposition of suspended mud in the deeper lake.

Lab. Number:	**CAMS-34550**
Field Number:	96900 LW 223PC 507-509 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.30
Material:	bulrush seed
Taxon Dated:	*Scirpus* sp. identified by A.M. Telka
Encl. Material:	noncalcareous clay mud
Latitude:	50° 39.4' N
Longitude:	96° 48.3' W
Elevation:	217.6 m (lake level); 201.7 m (sample elevation)
Locality:	central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	3280 ± 60 yr BP
Significance:	age of early Lake Winnipeg sediments overlying Agassiz Unconformity in South Basin
Assoc. Dates:	CAMS-17434 4040 ± 70 yr BP; CAMS-34551 4000 ± 60 yr BP; CAMS-46186 4030 ± 50 yr BP
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 97-13
Analyst:	A.M. Telka

Stratigraphy: 7.39 m lake sediment (6.78 m of Lake Winnipeg mud over 0.1 m of silty peat and 0.52 m of crumbly organic silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 9.75 m water depth. Dated bulrush seed is from the base of the uppermost unit of noncalcareous clay mud (0-509 cm) overlying silty clay mud, approximately 1.68 m above the Agassiz Unconformity at 677.5 cm down-core. Silty peat and organic silty clay are present below the unconformity. This is a replicate of core 94900 [illegible] 22a. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka): Preservation of bulrush seed is excellent with two long basal filaments and intact, pristine, style tip. This dated sample contains one of the richest and most diverse assemblages of plant and insect macrofossils examined in the *Namao* 96900 cores. Plant macrofossil assemblage includes many cat-tail (*Typha* sp.) fragments and well preserved bulrushes (*Scirpus* spp.) along with a variety of shoreline plants. Insect fossil assemblage contains many well preserved shoreline types and an increase in marsh beetles (Helodidae). The combined fossil evidence suggests a shallow marsh environment with shoreline near the core site at 3.3 ka. The present Lake Winnipeg shoreline is approximately 10 km away to the east and west and 30 km to the south.

Lab. Number:	**CAMS-34551**
Field Number:	96900 LW 223PC 661-666 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.30
Material:	bulrush seed
Taxon Dated:	*Scirpus* sp. identified by A.M. Telka
Encl. Material:	calcareous silty clay mud
Latitude:	50° 39.4' N
Longitude:	96° 48.3' W
Elevation:	217.6 m (lake level); 200.2 m (sample elevation)
Locality:	central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	4000 ± 60 yr BP
Significance:	age for basal Lake Winnipeg sedimentation in South Basin
Assoc. Dates:	CAMS-17434 4040 ± 70 yr BP; CAMS-34550 3280 ± 60 yr BP; CAMS-46186 4030 ± 50 yr BP
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume

Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-14
Analyst: A.M. Telka

Stratigraphy: 7.39 m lake sediment (6.78 m of Lake Winnipeg mud over 0.1 m of silty peat and 0.52 m of crumbly organic silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 9.75 m water depth. Dated bulrush seed is from calcareous Lake Winnipeg silty clay mud approximately 0.11 m above Agassiz Unconformity at 677.5 cm down-core. Silty peat and organic silty clay are present below the unconformity. This is a replicate of core 94900-122a. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): Preservation of dated bulrush seed is fair (remnant basal filaments, style tip worn). Plant macrofossils are minimally represented, insects are rare. The combined plant macrofossil and insect fossil evidence suggests that the shoreline was near the core site at 4.0 ka. The present Lake Winnipeg shoreline is approximately 10 km away to the east and west and 30 km to the south, indicating significant expansion and deepening of the lake in this area over the past 4000 radiocarbon years.

Lab. Number: **CAMS-34552**
Field Number: 94307-010 132-142 cm below beach surface
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, D. Frobel
Collected: 1994.09.10
Material: willow twig
Taxon Dated: *Salix* sp. identified by A.M. Telka
Encl. Material: peat
Latitude: 51° 51.3' N
Longitude: 97° 15.4' W
Elevation: 217.7 m (lake level); 216.4 m (sample elevation)
Locality: near Passage Point, western shore of Fisher Bay, southern North Basin, Lake Winnipeg
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 1020 ± 50 yr BP
Significance: age estimate for lake-level change
Assoc. Dates:
References: Forbes & Frobel, 1996; Vance & Telka, 1998; Forbes, D.L., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-02
Analyst: A.M. Telka

Stratigraphy: 1.55 m Hiller core taken through beachface at an eroding coastal site. Core stratigraphy consisted of 10 cm sand over 133 cm of peat resting on stiff blue clay.

Comments (A.M. Telka & D.L. Forbes): This delicate twig of willow (*Salix* sp. with bark intact) is from near the base of the peat unit, 1.0 m below mean lake level. It provides an age estimate of 1.0 ka for lower lake level at this site. The plant macrofossil assemblage is diverse, containing both shoreline and terrestrial components such as larch (*Larix* sp.) and spruce (*Picea* sp.) needles, birch (Betulaceae) seeds, alder (*Alnus* sp.) seeds and bracts, as well as sedge (*Carex* spp.), cat-tail (*Typha* sp.) and moss fragments. Insect fossils are rare. The peat unit is interpreted to have accumulated vertically in a backshore setting before being truncated at the present shoreline and buried beneath a thin transgressive beach veneer.

Lab. Number: **CAMS-34553**
Field Number: 94307-003 70-79 cm below ground surface
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, D. Frobel
Collected: 1994.09.08
Material: 21 cinquefoil seeds
Taxon Dated: *Potentilla norvegica* L. identified by A.M. Telka
Encl. Material: peaty mud
Latitude: 53° 49.9' N

Longitude:	98° 42.5' W
Elevation:	216.4 m (sample elevation)
Locality:	near head of Limestone Bay behind north shore of North Basin, Lake Winnipeg
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	930 ± 90 yr BP
Significance:	age of Limestone Point spit and beach ridges at head of Limestone Bay
Assoc. Dates:	
References:	Forbes & Frobel, 1996; Vance & Telka, 1998; Forbes, D.L., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 98-01
Analyst:	A.M. Telka

Stratigraphy: 1.00 m Hiller core comprising muddy peat (0-38 cm) and organic-rich silty mud (38-81 cm) overlying poorly sorted silty medium sand.

Comments (A.M. Telka & D.L. Forbes): This date of 0.9 ka on cinquefoil (*Potentilla norvegica* L.) seeds from near the base of a firm organic-rich mud unit provides a minimum age for the inner part of the beach-ridge complex, represented by the sand at the base of the core, and for early growth of the Limestone Point spit (Forbes, this volume). Plant and insect macrofossil assemblage from this dated interval is typical of a shoreline environment with abundant cat-tail (*Typha* sp.), many species of sedges (*Carex* spp.), cinquefoil (*Potentilla norvegica* L.) and mosses (*Sphagnum* sp.), as well as insects that live near water including ground beetles (*Bembidion* sp.) and rove beetles (Staphylinidae).

Lab. Number:	**CAMS-34554**
Field Number:	96900 LW 215PC 321.5 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.28
Material:	bulrush seed
Taxon Dated:	*Scirpus* sp. identified by A.M. Telka
Encl. Material:	silt-clay mud
Latitude:	51° 22.5' N
Longitude:	96° 34.3' W
Elevation:	218.1 m (lake level); 203.3 m (sample elevation)
Locality:	Washow Bay, central Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	3950 ± 60 yr BP
Significance:	age estimate for Lake Winnipeg sediments above Agassiz Unconformity in this part of the lake
Assoc. Dates:	CAMS-34555 4030 ± 50 yr BP
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 97-06
Analyst:	A.M. Telka

Stratigraphy: 4.85 m lake sediment (3.61 m of Lake Winnipeg mud over 1.24 m of Lake Agassiz sediment) recovered with a 10 cm diameter by 9 m long piston corer in 11.6 m water depth. Dated bulrush seed lies within Lake Winnipeg silty clay mud, approximately 0.40 m above the Agassiz Unconformity, which is underlain by firm crumbly calcareous clay mud. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): Preservational state of dated bulrush seed is fair (delicate basal bristles absent), however the remaining plant macrofossil and insect fossil assemblage shows no sign of redeposition. This sample has a richer insect assemblage than the lower dated interval (see CAMS-34555), with more shoreline-type insects including leafhoppers (Cicadellidae) and leaf beetles (Chrysomelidae: *Donacia* sp.) The combined sedimentological and fossil evidence demonstrates that the Agassiz Unconformity at this site was cut prior to about 4.0 ka, when the shoreline was closer to the core site than it is today.

Lab. Number: **CAMS-34555**
Field Number: 96900 LW 215PC 348 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.28
Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: silt-clay mud
Latitude: 51° 22.5' N
Longitude: 96° 34.3' W
Elevation: 218.1 m (lake level); 203.1 m (sample elevation)
Locality: Washow Bay, central Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 4030 ± 50 yr BP
Significance: age estimate for Lake Winnipeg sediments overlying Agassiz Unconformity
Assoc. Dates: CAMS-34554 3950 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-07
Analyst: A.M. Telka

Stratigraphy: 4.85 m lake sediment (3.61 m of Lake Winnipeg mud over 1.24 m of Lake Agassiz sediment) recovered with a 10 cm diameter by 9 m long piston corer in 11.6 m water depth. Dated bulrush seed lies within Lake Winnipeg silty clay mud, approximately 0.13 m above erosional contact at Agassiz Unconformity, which is underlain by firm crumbly calcareous clay. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): Preservational state of dated bulrush seed is good, with remnants of basal bristles intact. Many of the fossils within this sample are well preserved. Plant macrofossils are more abundant than insect fossils and include both shoreline and aquatic plants, the most abundant being well preserved bulrush (*Scirpus* sp.) seeds. Complete mollusc shells (both snails and clams) are also very abundant. The combined plant and insect macrofossil and sedimentological evidence demonstrates that the Agassiz Unconformity at this site was cut prior to 4.0 ka, when the shoreline was closer to the core site than it is today.

Eight samples from Lake Winnipeg sediment were examined in core 215, beginning with basal unit above the unconformity and extending up to 195 cm core depth. The combined plant macrofossil and insect fossil evidence suggests that, with the onset of Lake Winnipeg sedimentation, the core site was shallow at 4.0 ka and the shoreline remained close to this site until 250 cm depth in core, after which the lake expanded and the shoreline moved away from the core site. Two shell samples were obtained from this core at 373-375 cm and 457-459 cm, both below the Agassiz Unconformity. These as-yet undated specimens were identified by E. Nielsen and B. McKillop as *Helisoma pilsbryi infracarinatum* Baker, 1932 (upper sample) and *Fossaria modicella* (Say, 1825) (lower sample).

Lab. Number: **CAMS-35494**
Field Number: 96900 LW 219PC 372-377 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.29
Material: terrestrial beetle parts
Taxon Dated: ground beetle (Carabidae) elytra: *Amara* sp., *Agonum* sp.; weevil (Curculionidae) elytron: *Hypera* sp.; ant head: Formicidae; click beetle pronotum: Elateridae identified by A.M. Telka
Encl. Material: mud and sand
Latitude: 50° 56.6' N
Longitude: 96° 41.0' W
Elevation: 217.8 m (lake level); 203.0 m (sample elevation)
Locality: South Basin (Pearson Reef), Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 1970 ± 170 yr BP

Significance: age of former beach and lagoon beneath Lake Winnipeg mud at Pearson Reef
Assoc. Dates: CAMS-32190 3060 ± 70 yr BP; CAMS-32193 4760 ± 70 yr BP; CAMS-35500 2940 ± 80 yr BP; CAMS-35495 3920 ± 70 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Forbes, D.L., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-09
Analyst: A.M. Telka

Stratigraphy: 4.39 m lake sediment (1.65 m of Lake Winnipeg clay mud over 0.93 m fine to medium sand with granules, rare pebbles, and mud interbeds over 1.81 m of interbedded coarse pebbly sand and silty clay mud) recovered with a 10 cm diameter by 9 m long piston corer in 10.5 m water depth. Dated insects are approximately 2.07 m below the top of the sand. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of sand (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This date was intended to provide an age for infilling of a small basin interpreted as a backbarrier lagoon behind the former spit along the east side of Pearson Reef shoal. The pebbly sand in the core is interpreted as barrier washover sediment interbedded with finer deposits accumulating between washover events. Preservational state of dated insect fossils is excellent. Insect fossils are abundant and well preserved in this assemblage and include fragile 'articulated' beetles (i.e. with body parts attached). Plant macrofossils are rare with only five cat-tail (*Typha* sp.) seeds and one goosefoot (*Chenopodium* sp.) seed. The relatively high number of insect fossils in this assemblage constitutes a marked taphonomic bias. It is unusual to find so few plant macrofossils in association with such a diverse insect assemblage. Because the insect fossils are well preserved and do not contain pitted or worn surfaces, it can be assumed that these fossils were deposited in a subaqueous environment (e.g. flushed from a nearby source and quickly deposited in sand). The age of 2.0 ka is younger than other dates obtained for the relict beach system at Pearson Reef, suggesting either continued growth of the spit as lake level rose (the adjacent barrier crest elevation is 205.9 m or 11.9 m below present mean lake level) or later reworking of the submerged spit shoal, such that the backbarrier lagoon fill is much younger than the spit and may include contributions of material from nearby higher shoreline sources.

Lab. Number: **CAMS-35495**
Field Number: 96900 LW 220PC 535-540 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.29
Material: five goosefoot seeds
Taxon Dated: *Chenopodium* spp. identified by A.M. Telka
Encl. Material: calcareous sand
Latitude: 50° 56.8' N
Longitude: 96° 40.9' W
Elevation: 217.8 m (lake level); 201.3 m (sample elevation)
Locality: Pearson Reef, approximately 5 km off Hecla Island, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -27 ‰
Normalized Age: 3920 ± 70 yr BP
Significance: age of former shoreface beneath Lake Winnipeg mud at Pearson Reef
Assoc. Dates: CAMS-32190 3060 ± 70 yr BP; CAMS-32193 4760 ± 70 yr BP; CAMS-35494 1970 ± 170 yr BP; CAMS-35500 2940 ± 80 yr BP; CAMS-46193 3870 ± 140 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Forbes, D.L. et al., this volume; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-11
Analyst: A.M. Telka

Stratigraphy: 5.53 m Lake Winnipeg sediment (4.07 m clay and silty clay mud with occasional sand interbeds over 1.46 m sand and gravel) recovered with a 10 cm diameter by 9 m long piston corer in 10.5 m water depth. Dated goosefoot seeds are 1.33 m below the top of fine calcareous sand with granules and occasional medium sand and pebbly gravel, overlain above sharp contact by 4.07 m of clay mud and silty clay mud with one 9 cm sand bed and other rare thin sand beds and inclusions. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of sand (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Dated goosefoot seeds are well preserved compared to the remaining macrofossils and organics within this sample, which contain pitted surfaces. Insect fossils are rare but mollusc fragments are abundant. This date of 3.9 ka provides an age estimate for shoreface sediments associated with the former beach at Pearson Reef.

Lab. Number: **CAMS-35496**
Field Number: 96900 LW 224PC 577-582 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.09.03
Material: sunflower seed
Taxon Dated: *Helianthus* sp. identified by A.M. Telka
Encl. Material: calcareous mud and sand
Latitude: 50° 33.0' N
Longitude: 96° 47.2' W
Elevation: 217.9 m (lake level); 202.9 m (sample elevation)
Locality: approximately 10 km from southern shoreline, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 3550 ± 70 yr BP
Significance: age of initial flooding over shore-zone sand deposit 10 km off present shoreline at south end of lake
Assoc. Dates: CAMS-35501 3570 ± 120 yr BP; CAMS-35615 4090 ± 60 yr BP; CAMS-46192 5350 ± 50 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-15
Analyst: A.M. Telka

Stratigraphy: 7.31 m Lake Winnipeg sediment (5.50 m clay and silty clay over 0.32 m interlaminated mud and sand over 1.49 m sand) recovered with a 10 cm diameter by 9 m long piston corer in 8.5 m water depth. Dated sunflower seed is from the base of 32 cm thick, organic-rich, interlaminated mud and sand unit with wood fragments and small gastropod shells, resting directly on a sharp contact underlain by fine to medium calcareous sand including some coarse sand with mud clasts and mollusc shells, the latter particularly abundant below 7.00 m down-core. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of calcareous sand unit (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): Most southerly core in *Namao* 94900 and 96900 series. Preservational state of sunflower (*Helianthus* sp.) seed is excellent. This assemblage has been minimally transported, as evidenced by the excellent preservational state of most of the macrofossils. Shoreline at 3.5 ka was much closer to the core site than modern shoreline (10 km away), based upon plant and insect macrofossil evidence. This date is a cross-check for comparison between an upland shoreline taxon (*Helianthus* sp.) and an aquatic emergent (*Scirpus* sp.; CAMS-35501) with an age difference of 20 ± 50 years and provides a good estimate for initial flooding and nearshore sedimentation over beach sand at this site.

Lab. Number: **CAMS-35497**
Field Number: 96900 LW 209PC 95-97cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.26
Material: ground juniper seed
Taxon Dated: *Juniperus communis* L. identified by A.M. Telka
Encl. Material: noncalcareous silt
Latitude: 52° 30.9' N
Longitude: 97° 34.8' W
Elevation: 217.7 m (lake level); 200.0 m (sample elevation)
Locality: north of Berens Island, 24 km from eastern shore of North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 3730 ± 70 yr BP
Significance: age for burial of Agassiz Unconformity in south-central North Basin
Assoc. Dates:

References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-04
Analyst: A.M. Telka

Stratigraphy: 1.65 m lake sediment (1.04 m Lake Winnipeg silty clay mud and silt over 0.61 m stiff Lake Agassiz silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 16.5 m water depth. Dated juniper seed is from 9 cm thick silt unit near the base of Lake Winnipeg sediment, 7 cm above Agassiz Unconformity, which is underlain by stiff, finely laminated, calcareous silty clay. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka): Insect fossils within this sample are abundant and diverse in relation to plant macrofossils. This sample is the richest observed from the North Basin. The insect assemblage contains many delicate fossils, both of aquatic types, including water boatmen (Corixidae), water scavenger beetles (Hydrophilidae), predaceous diving beetles (*Colymbetes* sp.), and numerous midges (Chironomidae), and of many shoreline types, including shore bugs (Saldidae), marsh beetles (Helodidae), leaf hoppers (Cicadellidae), and jumping plant lice (Psyllidae). Interestingly this sample also contains fossils of the bark beetle (Scolytidae) indicating the presence of trees nearby. Plant macrofossils comprise mostly cat-tail (*Typha* sp.) and a few spruce (*Picea* sp.) needle fragments and the dated ground juniper seed (*Juniperus communis* L.). The preservational state of the plant and insect macrofossils within this sample is excellent. The combined plant macrofossil and insect fossil evidence suggests a shallow marsh environment with shoreline close to the core site at 3.7 ka.

Lab. Number: **CAMS-35498**
Field Number: 96900 LW 217PC 127-132 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.28
Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: silt-clay mud
Latitude: 51° 08.0' N
Longitude: 96° 35.1' W
Elevation: 218.1 m (lake level); 205.8 m (sample elevation)
Locality: between Black and Hecla Islands, northern South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 3340 ± 50 yr BP
Significance: age of upper unconformity over local depression in Agassiz Unconformity on Hecla-Black Sill
Assoc. Dates: CAMS-46190 3340 ± 40 yr BP; CAMS-46191 3910 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Forbes, D.L. et al., this volume; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-08
Analyst: A.M. Telka

Stratigraphy: 3.10 m lake sediment recovered with a 10 cm diameter by 9 m long piston corer in 11.1 m water depth. Dated bulrush seed is from Lake Winnipeg silty clay mud directly above upper sharp contact at 1.32 m down-core. This is underlain by 1.70 m of firm crumbly silty clay (non-calcareous in upper part and calcareous in lower) over a lower erosional unconformity at 3.02 m down-core, interpreted as the Agassiz Unconformity. This second contact is underlain by stiff, calcareous, silty clay. Sample elevation is based on acoustic profile and seismic reflection travel time to the lower unconformity (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This date together with CAMS-46190 (also 3.3 ka) gives an age for the upper of two unconformities on the Hecla-Black Sill. This contact is interpreted as erosional truncation of infill sediments in a local depression (possible channel) cut into the underlying Agassiz Sequence deposits prior to 3.9 ka (CAMS-46191). Preservational state of dated bulrush seed is excellent with basal bristles intact. This deposit contains many well preserved macrofossil seeds with the majority of the plants being shoreline inhabitants. Insect fossils are minimally represented with both aquatic and shoreline components.

Lab. Number: **CAMS-35499**
Field Number: 96900 LW 201PC 434-439 cm below top of cored sediment

Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.22
Material: charred spruce needles
Taxon Dated: *Picea* sp. identified by A.M. Telka
Encl. Material: silty clay mud
Latitude: 53° 12.0′ N
Longitude: 99° 06.9′ W
Elevation: 217.8 m (lake level); 199.5 m (sample elevation)
Locality: approximately 13 km off Grand Rapids, western North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 4800 ± 70 yr BP
Significance: age estimate for Agassiz Unconformity and Saskatchewan River diversion
Assoc. Dates:
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume; Ritchie & Hadden, 1975
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-01
Analyst: A.M. Telka

Stratigraphy: 5.25 m lake sediment (4.39 m Lake Winnipeg silt-clay mud over 0.86 m stiff, laminated, Lake Agassiz silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 13.0 m water depth. Dated spruce needles are from basal Lake Winnipeg sediment immediately above an erosional contact, the Agassiz Unconformity, which is underlain by stiff, finely laminated, silty clay with a dry, crumbly, blocky fractured character in upper 20 cm below the contact. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Preservational state of the spruce needle macrofossils is poor (two charred fragments, one is slightly charred) suggesting the needles were transported some distance prior deposition. The combined plant and insect macrofossil evidence suggest that the shoreline at 4.8 ka was no nearer to the core site than it is today. Although this interval does not represent an *in situ* deposit, the dated spruce needles can be interpreted as representing an age for the beginning of Lake Winnipeg sedimentation over an erosional surface cut in Lake Agassiz sediment which was formerly exposed above lake level.

Lab. Number: **CAMS-35500**
Field Number: 96900 LW 219PC 436-439 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.29
Material: raspberry seeds
Taxon Dated: *Rubus idaeus* L. identified by A.M. Telka
Encl. Material: mud and sand
Latitude: 50° 56.6′ N
Longitude: 96° 41.0′ W
Elevation: 217.8 m (lake level); 202.3 m (sample elevation)
Locality: South Basin (Pearson Reef), Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 2940 ± 80 yr BP
Significance: age of paleobeach and lagoon at Pearson Reef
Assoc. Dates: CAMS-32190 3060 ± 70 yr BP; CAMS-32193 4760 ± 70 yr BP; CAMS-35494 1970 ± 170 yr BP; CAMS-35495 3920 ± 70 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Forbes, D.L., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-10
Analyst: A.M. Telka

Stratigraphy: 4.39 m lake sediment (1.65 m of Lake Winnipeg clay mud over 0.93 m fine to medium sand with granules, rare pebbles, and mud interbeds over 1.81 m of interbedded coarse pebbly sand and silty clay mud) recovered with a 10 cm diameter by 9 m long piston corer in 10.5 m water depth. Dated raspberry seeds are from the base of the core, 2.74 m below the top of the sand. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of sand (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This date was intended to provide an age for infilling of a small basin interpreted as a backbarrier lagoon behind the former spit along the east side of Pearson Reef shoal. The pebbly sand in the core is interpreted as barrier washover sediment interbedded with finer deposits accumulating between washover events. Preservational state of dated raspberry (*Rubus idaeus* L.) seed and fragments is poor. Plant macrofossil assemblage comprises mostly *Potentilla paradoxa* Nutt and goosefoot seeds (*Chenopodium* sp.) as well as a few other shoreline inhabitants. Insect fossil assemblage is more varied with both aquatic species (e.g. water strider [Gerridae] and predaceous diving beetles [Dytiscidae]) and many shoreline types. The combined macrofossil evidence suggests that the shoreline is near the core site, consistent with the seismic reflection profile interpretation and core lithology. The age of 2.9 ka is older than the 2.0 ka insect assemblage 70 cm higher in the core (CAMS-35494) and between 0.1 and 1.0 ka younger than other dates obtained for the relict beach system at Pearson Reef (CAMS-32190 and CAMS-35495; note that the older age for CAMS-32193 incorporates a reservoir error), suggesting that the Pearson Reef spit developed between 3.9 and 2.9 ka.

Lab. Number: **CAMS-35501**
Field Number: 96900 LW 224PC 577-582 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.09.03
Material: two bulrush seeds
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: Lake Winnipeg sandy mud with organics
Latitude: 50° 33.0' N
Longitude: 96° 47.2' W
Elevation: 217.9 m (lake level); 202.9 m (sample elevation)
Locality: approximately 10 km from southern shoreline, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 3570 ± 120 yr BP
Significance: age of submerged paleoshoreline
Assoc. Dates: CAMS-35496 3550 ± 70 yr BP; CAMS-35615 4090 ± 60 yr BP; CAMS-46192 5350 ± 50 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-15
Analyst: A.M. Telka

Stratigraphy: 7.31 m Lake Winnipeg sediment (5.50 m clay and silty clay over 0.32 m interlaminated mud and sand over 1.49 m sand) recovered with a 10 cm diameter by 9 m long piston corer in 8.5 m water depth. Dated bulrush seed is from the base of 32 cm thick, organic-rich, interlaminated calcareous silt-clay mud and sand unit with wood fragments and small gastropod shells, resting directly on a sharp contact underlain by fine to medium calcareous sand including some coarse sand with mud clasts and mollusc shells, the latter particularly abundant below 7.00 m down-core. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of calcareous sand unit (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): Most southerly core in *Namao* 94900 and 96900 core series. Preservational state of dated *Scirpus* sp. seeds is good with remnant basal bristles still attached as well as pristine style tip. This assemblage has been minimally transported as evidenced by the excellent preservational state of most of the macrofossils. Shoreline at 3.5 ka was much closer to the core site than modern shoreline (10 km away), based on plant and insect macrofossil evidence. This date is a cross-check for comparison between aquatic emergent (*Scirpus* sp.) and upland shoreline (*Helianthus* sp.; CAMS-35496) taxa with an age difference of 20 ± 50 years and provides a good estimate for the initial flooding and nearshore sedimentation over beach sand at this site.

Lab. Number: **CAMS-35615**
Field Number: 96900 LW 224PC 705-710 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis

Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.09.03
Material: shell
Taxon Dated: unidentified pelecypod valve
Encl. Material: highly calcareous sand
Latitude: 50° 33.0' N
Longitude: 96° 47.2' W
Elevation: 217.9 m (lake level); 201.6 m (sample elevation)
Locality: approximately 10 km from southern shoreline, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -7 ‰
Normalized Age: 4090± 60 yr BP
Significance: age of submerged paleoshoreline
Assoc. Dates: CAMS-3546 3550 ± 70 yr BP; CAMS-35501 3570 ± 120 yr BP; CAMS-46192 5350 ± 50 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-16
Analyst: A.M. Telka

Stratigraphy: 7.31 m Lake Winnipeg sediment (5.50 m clay and silty clay over 0.32 m interlaminated mud and sand over 1.49 m sand) recovered with a 10 cm diameter by 9 m long piston corer in 8.5 m water depth. Dated pelecypod valve is from zone of abundant shell material near base of calcareous sand in core, approximately 1.25 m below sharp contact at the top of this sand. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of calcareous sand unit (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): Preservational state of dated shell is good with periostracum intact. Plant and insect macrofossil assemblage is mostly shoreline and emergent plants with both terrestrial and aquatic insect components. This shell age of 4.1 ka is approximately 0.5 ka older than the overlying dated *Scirpus* sp. and *Helianthus* sp. seeds (3.6 ka), suggesting a reservoir correction of <500 years. This date suggests an age younger than 4.0 ka for deposition of the shelly sand, interpreted as a beach deposit, in the base of this core.

Lab. Number: **CAMS-35616**
Field Number: 96900 LW 221PC 526-527 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.09.03
Material: pelecypod shell
Taxon Dated: *Sphaerium striatinum* Lamarck
Encl. Material: highly calcareous stiff crumbly clay
Latitude: 50° 56.1' N
Longitude: 96° 37.0' W
Elevation: 217.9 m (lake level); 201.0 m (sample elevation)
Locality: approximately 9 km from eastern shoreline, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -7 ‰
Normalized Age: 4320 ± 50 yr BP
Significance: age of Agassiz Unconformity
Assoc. Dates: CAMS-38680 4190 ± 100 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-12
Analyst: A.M. Telka

Stratigraphy: 5.78 m lake sediment (5.22 m Lake Winnipeg silt-clay mud over 0.56 m Lake Agassiz calcareous clay) recovered with a 10 cm diameter by 9 m long piston corer in 10.4 m water depth. Dated shell (collected in growth position) is from immediately beneath sharp erosional contact representing the Agassiz Unconformity , which is underlain by 40 cm of stiff, crumbly, highly calcareous clay over stiff, non-crumbly, calcareous clay extending to base of core. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This and an associated date on a *Scirpus* sp. seed (CAMS-3860) are interpreted to indicate an age of about 4.2 ka for initial flooding over the former subaerial surface represented by the Agassiz Unconformity at this site and the approximate age for a climate shift to wetter conditions enabling development of the lake in the South Basin (Lewis et al., this volume). Preservational state of the pelecypod shell is excellent. This shell was chosen for AMS dating for comparison with the associated date on terrestrial plant material (*Scirpus* sp. seed). The shell date of 4.3 ka is approximately 0.13 ka older, suggesting a 'hard-water' correction of at least 100 years.

Lab. Number: **CAMS-38675**
Field Number: 94900 LW 106 PC 174-179 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis, C.G. Rodrigues
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1994.08.23
Material: ostracodes
Taxon Dated: *Candona rawsoni* Tressler and *Candona subtriangulata* Benson and MacDonald identified by C.G. Rodrigues
Encl. Material: moderately calcareous clay-silt mud
Latitude: 53° 34.70' N
Longitude: 98° 05.83' W
Elevation: 217.60 m (lake level); 199.0 m (sample elevation)
Locality: approximately 20 km from Warren Landing, northeast North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -5 ‰
Normalized Age: 6900 ± 80 yr BP
Significance: age estimate for basal coarse facies of Lake Winnipeg sediment
Assoc. Dates: CAMS-32191 6910 ± 200 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:
Analyst: C.G. Rodrigues

Stratigraphy: 7.89 m lake sediment (182 cm of Lake Winnipeg mud over 607 cm of Lake Agassiz sediments) recovered with a 10 cm diameter by 9 m long piston corer in 16.8 m water depth. Dated ostracodes are from 3 to 8 cm above the Agassiz Unconformity in a 23 cm thick unit of soft, moderately calcareous, clay-silt mud with silt and sand, directly overlying erosional contact with the underlying firm silty clay rhythmites deposited in Lake Agassiz. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Duplicate sample redated to reduce large uncertainty in CAMS-32191. Date of 6.9 ka provides an age estimate for the basal coarse facies of Lake Winnipeg sediment in the northeast North Basin of the lake.

Lab. Number: **CAMS-38676**
Field Number: 96900 LW 204PC 362-373 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis, C.G. Rodrigues
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.24
Material: ostracodes
Taxon Dated: *Candona rawsoni* Tressler and *Candona subtriangulata* Benson and MacDonald identified by C.G. Rodrigues
Encl. Material: calcareous silty clay mud
Latitude: 53° 34.0' N
Longitude: 98° 06.3' W
Elevation: 217.8 m (lake level); 198.2 m (sample elevation)
Locality: approximately 20 km from Warren Landing, northeast North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -5 ‰
Normalized Age: 6700 ± 80 yr BP
Significance: age of Lake Winnipeg sediments
Assoc. Dates: CAMS-38678 6750 ± 70 yr BP; CAMS-38675 6900 ± 80 yr BP

References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	
Analyst:	C.G. Rodrigues

Stratigraphy: 5.79 m Lake Winnipeg sediment recovered with a 10 cm diameter by 9 m long piston corer in 15.9 m water depth. Dated ostracode interval lies within a unit of soft, calcareous, silty clay mud with occasional sharp-based laminae of silt and fine sand, conformably overlain by 3.30 m of soft clay mud. Because this core did not penetrate a sharp unconformity with underlying Lake Agassiz sediments, the sample elevation is based on lake level at the time of coring, water depth, and depth in core.

Comments (A.M. Telka & D.L. Forbes): The dated ostracodes are from calcareous silty clay mud and susceptible to hard-water effects from old carbon within the watershed and are likely a few hundred years younger than the age determined here. These dates on early Lake Winnipeg sediments in core 204 are reasonably consistent with the date of 6.9 ka on similar ostracodes (*Candona rawsoni* and *C. subtriangulata*) in a coarse-grained basal unit of Lake Winnipeg sediments in nearby core 106 (see CAMS-38675).

Lab. Number:	**CAMS-38677**
Field Number:	96900 LW 207PC 155-163 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis, C.G. Rodrigues
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.26
Material:	ostracodes
Taxon Dated:	*Candona rawsoni* Tressler identified by C.G. Rodrigues
Encl. Material:	stiff weakly calcareous silty Agassiz clay
Latitude:	52° 51.6' N
Longitude:	97° 51.2' W
Elevation:	217.7 m (lake level); 198.5 m (sample elevation)
Locality:	north of George Island, North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-5 ‰
Normalized Age:	9170 ± 70 yr BP
Significance:	age of Lake Agassiz sediments
Assoc. Dates:	
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	
Analyst:	C.G. Rodrigues

Stratigraphy: 3.34 m lake sediment (1.24 m Lake Winnipeg silty clay mud over 2.10 m Lake Agassiz silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 17.1 m water depth. Dated ostracodes lie 0.31 m below the Agassiz Unconformity in stiff, weakly calcareous, silty clay, rhythmically laminated below about 1.60 m down-core. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka): This age of 9.2 ka for ostracodes is the oldest date obtained in the Lake Winnipeg core series and provides an age for Lake Agassiz sediments below the unconformity at this point in the lake.

Lab. Number:	**CAMS-38678**
Field Number:	96900 LW 204PC 513-518 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.24
Material:	spruce needle
Taxon Dated:	*Picea* sp. identified by A.M. Telka
Encl. Material:	calcareous mud and silt laminations of Lake Winnipeg
Latitude:	53° 34.0' N
Longitude:	98° 06.3' W
Elevation:	217.8 m (lake level); 196.8 m (sample elevation)

Locality:	approximately 20 km from Warren Landing, northeast North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	6750 ± 70 yr BP
Significance:	age of Lake Winnipeg sediments
Assoc. Dates:	CAMS-38676 6700 ± 80 yrs BP
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 97-03
Analyst:	A.M. Telka

Stratigraphy: 5.79 m Lake Winnipeg sediment recovered with a 10 cm diameter by 9 m long piston corer in 15.9 m water depth. Dated spruce needle lies within a unit of soft, calcareous, silty clay mud with occasional sharp-based laminae of silt and fine sand, conformably overlain by 3.30 m of soft clay mud. Because this core did not penetrate a sharp unconformity with underlying Lake Agassiz sediments, the sample elevation is based on lake level at the time of coring, water depth, and depth in core.

Comments (A.M. Telka): Preservational state of spruce (*Picea* sp.) needle fragment (5.5 mm length) is poor . This partially charred fragment has neither base nor tip, suggesting long-distance transport before final deposition. Plant macrofossils in this sample are rare with only one well preserved cat-tail (*Typha* sp.) seed, charred moss fragment and the dated spruce needle fragment. Insect fossils are also rare with minimal representation of shoreline type insects. Shoreline at 6.8 ka was probably not significantly nearer than it is today.

Lab. Number:	**CAMS-38679**
Field Number:	96900 LW 214PC 298-303 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.27
Material:	wood
Taxon Dated:	unidentifiable
Encl. Material:	noncalcareous silty clay mud
Latitude:	51° 56.1' N
Longitude:	96° 59.1' W
Elevation:	217.8 m (lake level); 203.2 m (sample elevation)
Locality:	north of The Narrows, approximately 9 km from nearest shoreline, southern North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	3630 ± 50 yr BP
Significance:	age of Lake Winnipeg sediments ~72 cm above Agassiz Unconformity
Assoc. Dates:	
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 97-05
Analyst:	A.M. Telka

Stratigraphy: 4.25 m lake sediment (3.75 m Lake Winnipeg silty clay mud over 0.50 m Lake Agassiz clayey silt) recovered with a 10 cm diameter by 9 m long piston corer in 11.3 m water depth. Dated wood lies within soft, non-calcareous, mottled (burrowed) and faintly laminated, silty clay mud, approximately 0.72 m above erosional Agassiz Unconformity, which is underlain by firm to stiff calcareous clayey silt with dropstones. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): This date indicates that backflooding had penetrated into this narrow southern portion of the North Basin prior to 3.6 ka. Preservational state of the wood fragment is fair, suggesting the wood was transported some distance prior to deposition. There is minimal representation of plant macrofossils within this sample with mosses and cat-tail (*Typha* sp.) comprising the assemblage. Insect fossils are also present in minimal numbers. Examination of the macrofossil assemblage 10 cm above this dated interval (288-293 cm) reveals an assemblage slightly richer and higher in numbers of cat-tail, mosses and marsh beetles (Helodidae), suggesting a lake-marginal or nearby marsh environment at 3.6 ka.

Lab. Number: **CAMS-38680**
Field Number: 96900 LW 221PC 523-528 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.09.03
Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: highly calcareous stiff crumbly clay
Latitude: 50° 56.1' N
Longitude: 96° 37.0' W
Elevation: 217.9 m (lake level)
Locality: approximately 9 km from eastern shoreline, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 4190 ± 100 yr BP
Significance: age of Agassiz Unconformity
Assoc. Dates: CAMS-35616 4320 ± 50 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 97-12
Analyst: A.M. Telka

Stratigraphy: 5.78 m lake sediment (5.22 m Lake Winnipeg silt-clay mud over 0.56 m Lake Agassiz calcareous clay) recovered with a 10 cm diameter by 9 m long piston corer in 10.4 m water depth. Dated bulrush seed is from crumbly zone immediately beneath sharp erosional contact representing the Agassiz Unconformity , which is underlain by 40 cm of stiff, crumbly, highly calcareous clay over stiff, non-crumbly, calcareous clay extending to base of core. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This and an associated date on a pelecypod bivalve from the same interval (see CAMS-35616) are interpreted to indicate an age of about 4.2 ka for initial flooding over the former subaerial surface represented by the Agassiz Unconformity at this site and the beginning of lake sedimentation in the South Basin (Lewis et al., this volume). The preservational state of the dated bulrush seed is fair.

Lab. Number: **CAMS-44526**
Field Number: 97301-007
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, L. Hopkinson
Collected: 1997.03.22
Material: 2.5 raspberry seeds
Taxon Dated: *Rubus idaeus* L. identified by A.M. Telka
Encl. Material: sand
Latitude: 52° 24.92' N
Longitude: 97° 06.94' W
Elevation: 220 m (sample elevation)
Locality: Disbrowe Point, north of Berens River, North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: modern
Significance: age of dune at neck of Disbrowe Point
Assoc. Dates: BGS-1910 130 ± 70 yr BP; BGS-1911 260 ± 75 yr BP;
CAMS-44527 2510 ± 50 yr BP; CAMS-44528 2910 ± 50 yr BP
References: Forbes, D.L., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-04
Analyst: A.M. Telka

Stratigraphy: Sample is from a buried soil horizon in the dunes on the neck of Disbrowe Point, approximately 2.4 m above lake-ice level at the time of sampling.

Comments (D.L. Forbes): The modern date on this sample demonstrates that dune migration on the lakeward half of the Disbrowe Point barrier at its narrowest part has been active in recent time. The driftwood ages from the face of the dune in this vicinity (see BGS-1910 and BGS-1911) show that washover trimmed the dune in at least one place here within the past 130 radiocarbon years.

Lab. Number: **CAMS-44527**
Field Number: 97301-008 5-7 cm below water-sediment interface
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, L. Hopkinson, F. Jodrey
Collected: 1997.03.22
Material: twig
Taxon Dated: unidentifiable
Encl. Material: firm black peat
Latitude: 52° 25.0617' N
Longitude: 97° 06.9650' W
Elevation: 217.7 m (lake level); 215.1 m (sample elevation)
Locality: off Disbrowe Point, north of Berens River, North Basin, Lake Winnipeg
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 2510 ± 50 yr BP
Significance: age estimate for submerged shoreline
Assoc. Dates: CAMS-44528 2910 ± 50 yr BP
References:
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-05
Analyst: A.M. Telka

Stratigraphy: 0.67 m sediment recovered from 1.07 m hammer core, 10 cm in diameter, taken through ice in 2.6 m water depth. Dated twig lies just below pebbly sand (0-5 cm) at the top of a 29 cm thick peat unit underlain by 15 cm of silt and granules over stiff Lake Agassiz clay.

Comments (D.L. Forbes & A.M. Telka): The age of 2.5 ka provides a maximum age for the termination of peat deposition at this site lakeward of the Disbrowe Point beach, at least 2.5 m below present lake level. It demonstrates landward retreat of the shoreline as lake level rose at the south end of the North Basin. Preservational state of the delicate dated twig with bark intact (indicating minimal transport) is excellent. Most of the organics within the dated peat unit consist of well preserved fragments of wood, some being identified as willow (*Salix* sp.). Macrofossil seeds and/or needles of larch (*Larix* sp.), birch (*Betula* sp.), alder (*Alnus incana*) and spruce (*Picea* sp.) dominate the assemblage with minor representation of shoreline taxa including heaths (*Chamaedaphne calyculata*) and cat-tail (*Typha* sp.). Insect macrofossil assemblage contains mostly hygrophilous type insects including many small articulated rove beetles (Staphylinidae), leaf beetles (*Chrysomela lineatopunctata* Forst.) which live on willow, poplar or alder, and marsh beetles (Helodidae).

Lab. Number: **CAMS-44528**
Field Number: 97301-008 33-34 cm below water-sediment interface
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, L. Hopkinson, F. Jodrey
Collected: 1997.03.22
Material: 70 mint seeds
Taxon Dated: *Mentha* sp. identified by A.M. Telka
Encl. Material: firm black peat
Latitude: 52° 25.0617' N
Longitude: 97° 06.9650' W
Elevation: 217.7 m (lake level); 214.8 m (sample elevation)
Locality: off Disbrowe Point, north of Berens River, North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 2910 ± 50 yr BP

Significance:	basal date on peat
Assoc. Dates:	CAMS-44527 2510 ± 50 yr BP
References:	Forbes, D.L., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 98-07
Analyst:	A.M. Telka

Stratigraphy: 0.67 m sediment recovered from 1.07 m hammer core, 10 cm in diameter, taken through ice in 2.6 m water depth. Dated mint seeds are from the base of 29 cm thick peat unit below surface 5 cm veneer of nearshore sand and underlain by 15 cm of silt and granules over stiff Lake Agassiz clay.

Comments (D.L. Forbes & A.M. Telka): The age of 2.9 ka provides a basal age estimate for initiation of peat accumulation at this site and dates the termination of shallow-water deposition of silt and granules overlying the Agassiz Unconformity, about 2.9 m below present lake level lakeward of the present beach on Disbrowe Point. Preservational state of the dated mint (*Mentha* sp.) seeds is excellent. Unlike the dated top portion of the peat unit (see CAMS-44527), in which most of the organics consist of wood, the unidentifiable organics within the base of the peat contain 'mats' of fine filamentous plant fragments. Shoreline indicators such as sedges (Cyperaceae), burreeds (*Sparganium* sp.), grasses (Gramineae) and mints (*Mentha* sp.) dominate the plant macrofossil assemblage with mints being the most abundant taxon. Tree species are near-absent, with only one seed of birch (*Betula* sp.) being observed. Insect remains comprise mostly taxa which live among shoreline plants, including rove beetles (*Olophrum rotundicolle*), a species found among sedges at edges of lakes, as well as bugs (Hemiptera) and marsh beetles (Helodidae).

Lab. Number:	**CAMS-44529**
Field Number:	97301-010 49-51 cm below water-sediment interface
Submitter(s):	D.L. Forbes
Collector(s):	D.L. Forbes, L. Hopkinson, F. Jodrey
Collected:	1997.03.24
Material:	bulrush seed
Taxon Dated:	*Scirpus* sp. identified by A.M. Telka
Encl. Material:	sand
Latitude:	51° 00.22' N
Longitude:	96° 52.24' W
Elevation:	217.7 m (lake level); 213.8 m (sample elevation)
Locality:	off Sandy Bar, southern Hecla Island, northern South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	1850 ± 50 yr BP
Significance:	age of shoreface deposition in northern South Basin
Assoc. Dates:	CAMS-46189 2190 ± 50 yr BP
References:	Forbes, D.L., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 98-14
Analyst:	A.M. Telka

Stratigraphy: 0.74 m sediment recovered from 1.18 m hammer core, 10 cm in diameter, taken through ice in 3.4 m water depth. Dated bulrush seed is from near the base of a 52 cm thick unit of ripple-laminated, calcareous, silty sand, approximately 3 cm above erosional contact representing the Agassiz Unconformity, which is underlain by firm silty clay.

Comments (D.L. Forbes & A.M. Telka): This sample provides an age on the deposition of parallel- and ripple cross-laminated silty sand approximately 3.9 m below present lake level, overlying the Agassiz Unconformity. Preservational state of the dated bulrush (*Scirpus* sp.) seed is fair retaining some vulnerable surface features. Plant and insect macrofossils are minimally represented and contain a few seeds of aquatic emergents, bulrushes and sedges as well as immature forms of aquatic insects.

Lab. Number:	**CAMS-44530**
Field Number:	97301-011 35-38 cm below water-sediment interface
Submitter(s):	D.L. Forbes
Collector(s):	D.L. Forbes, L. Hopkinson, F. Jodrey

Collected: 1997.03.24
Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: muddy peat
Latitude: 51° 00.98' N
Longitude: 96° 52.29' W
Elevation: 217.7 m (lake level); 215.1 m (sample elevation)
Locality: behind Sandy Bar in Grassy Narrows, northern South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 370 ± 70 yr BP
Significance: age of backbarrier marsh formation and submergence
Assoc. Dates:
References: Forbes, D.L., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-16
Analyst: A.M. Telka

Stratigraphy: 0.74 m sediment recovered from 1.59 m hammer core, 10 cm in diameter, taken through ice in 2.2 m water depth. Dated bulrush seed is from a thin unit of muddy peat directly above erosional contact representing the Agassiz Unconformity at 0.38 m down-core, and underlain by firm silty clay.

Comments (D.L. Forbes & A.M. Telka): This sample provides an age on muddy peat deposition in a backbarrier embayment about 2.6 m below present lake level in the northern South Basin of Lake Winnipeg. It is anomalously young for a shoreline date at that elevation, suggesting that the material may be reworked from marshy shores nearby. Preservational state of the dated bulrush (*Scirpus* sp.) seed is fair with remnants of basal filaments intact. Although the muddy peat contains an abundance of fossil remains, preservation varies greatly with most of the macrofossil seeds displaying worn flattened surfaces, many of them being fragmented. Plant macrofossil assemblage is diverse containing abundant shoreline, aquatic emergent and submergent plants. Insect fossils are not as diverse and are represented mostly by aquatic forms.

Lab. Number: **CAMS-44531**
Field Number: 97301-014 48-50 cm below water-sediment interface
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, F. Jodrey
Collected: 1997.03.25
Material: 31 cursed crowfoot seeds
Taxon Dated: *Ranunculus sceleratus* L. identified by A.M. Telka
Encl. Material: peat
Latitude: 50° 44.07' N
Longitude: 96° 32.90' W
Elevation: 217.6 m (lake level); 212.7 m (sample elevation)
Locality: off Elk Island, South Basin, Lake Winnipeg
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 1800 ± 60 yr BP
Significance: age of submerged peat
Assoc. Dates: CAMS-46194 1420 ± 60 yr BP; GSC-1977 1660 ± 60 yr BP;
GSC-1980 1060 ± 210 yr BP
References: Forbes, D.L., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-21
Analyst: A.M. Telka

Stratigraphy: 0.87 m sediment recovered from 1.26 m hammer core, 10 cm in diameter, taken through ice in 4.4 m water depth. Dated cursed crowfoot seeds are from the base of a 41 cm thick unit of laminated woody peat resting directly on sharp erosional contact representing the Agassiz Unconformity at 0.51 m down-core and underlain by stiff, calcareous, silty clay.

Comments (D.L. Forbes & A.M. Telka): This date provides an age estimate for the beginning of peat accumulation at this site, immediately overlying the Agassiz Unconformity, approximately 4.9 m below lake level at the time of sampling. The dated peat may have accumulated in a backbarrier depression similar to that inferred for GSC-1977 and GSC-1980, or may be coextensive with the peat represented by those dates. Preservational state of the dated cursed crowfoot (*Ranunculus sceleratus*) seeds is good. Fossil remains from the peat are diverse and abundant with the majority of plant macrofossil seeds being shoreline taxa. Plant remains (in order of abundance) include grasses (Gramineae), mints (*Mentha* sp.), sedges (Cyperaceae), the dated cursed crowfoot (*Ranunculus sceleratus*), and many other taxa. Insect fossils are less diverse and include shoreline dwellers along with aquatic immature forms.

Lab. Number:	**CAMS-46186**
Field Number:	96900 LW 223PC 721-726 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.30
Material:	bulrush seed
Taxon Dated:	*Scirpus* sp. identified by A.M. Telka
Encl. Material:	organic silty clay
Latitude:	50° 39.4' N
Longitude:	96° 48.3' W
Elevation:	217.6 m (lake level); 199.6 m (sample elevation)
Locality:	central South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	4030 ± 50 yr BP
Significance:	initiation of Lake Winnipeg sedimentation in South Basin
Assoc. Dates:	CAMS-34550 3280 ± 60 yr BP; CAMS-17434 4040 ± 70 yr B.P
References:	Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa:	See Plant and Insect Macrofossil Report MFRPT 98-31
Analyst:	A.M. Telka

Stratigraphy: 7.39 m lake sediment (6.78 m of Lake Winnipeg mud over 0.1 m of silty peat and 0.52 m of crumbly organic silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 9.75 m water depth. Dated bulrush seed is from an organic-rich ball in silty clay, approximately 44 cm below the base of soft mud. Silty peat and organic silty clay are present below the unconformity, as well as a basal unit of sucked-in soft mud (recored material). This is a replicate of core 94900-122a. Sample elevation is based on acoustic profile and seismic reflection travel time to the base of soft mud (Lewis et al., this volume).

Comments (A.M. Telka & D.L. Forbes): Preservation state of the dated bulrush seed is good. Organics within this interval are in ball form with the surrounding sediment being firm, crumbly, Lake Agassiz silty clay. It is therefore probable that the sample post-dates Lake Agassiz deposition, but was introduced at depth either through subaerial cracks in the Agassiz surface (see BGS-1477), by ice scour disturbance, or in the coring process. The date of 4.0 ka provides an age estimate for the beginning of Lake Winnipeg sedimentation in the South Basin.

Lab. Number:	**CAMS-46187**
Field Number:	96900 LW 213PC 10-15 cm below top of cored sediment
Submitter(s):	L.H. Thorleifson, C.F.M. Lewis
Collector(s):	GSC & MGSB scientists on CCGS *Namao*
Collected:	1996.08.27
Material:	spruce needle
Taxon Dated:	*Picea* sp. identified by A.M. Telka
Encl. Material:	noncalcareous silty clay mud
Latitude:	51° 52.5' N
Longitude:	96° 56.5' W
Elevation:	217.8 m (lake level); 204.3 m (sample elevation)
Locality:	north of The Narrows, southern North Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	
$\delta^{13}C$:	-25 ‰
Normalized Age:	2540 ± 60 yr BP

Significance: basal date on Lake Winnipeg sediment
Assoc. Dates:
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-33
Analyst: A.M. Telka

Stratigraphy: 1.43 m lake sediment (0.15 m Lake Winnipeg silty clay mud over 1.28 m Lake Agassiz clay and silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 11.5 m water depth. Dated spruce needle is from basal Lake Winnipeg mud directly overlying sharp erosional contact with trace of grit, representing the Agassiz Unconformity, underlain by stiff, fractured, non-calcareous clay in upper 30 cm below contact and stiff, finely laminated, calcareous silty clay below that. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (A.M. Telka): This date of 2.5 ka provides an age estimate for the onset of Lake Winnipeg sedimentation in the southern part of the North Basin. Preservational state of the dated spruce needle fragment is poor (5 mm in length with needle tip intact, no base). Plant macrofossils within this sample are sparse and include a single seed of cat-tail (*Typha* sp.) and one well preserved arboreal birch seed (*Betula* sp.). Insect fossils are minimally represented and include mostly aquatic immatures of mayflies (Ephemeroptera), midges (Chironomidae) and water fleas (*Daphnia* sp.).

Lab. Number: **CAMS-46188**
Field Number: 96900 LW 222PC 735-740 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS Namao
Collected: 1996.09.03
Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: calcareous silty clay
Latitude: 50° 56.1' N
Longitude: 96° 44.2' W
Elevation: 217.9 (lake level); 200.0 m (sample elevation)
Locality: south of Hecla Island, northern South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 4710 ± 50 yr BP
Significance: age estimate on basal sedimentation in South Basin
Assoc. Dates:
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-37
Analyst: A.M. Telka

Stratigraphy: 7.86 m lake sediment (7.35 m Lake Winnipeg clay and silty clay mud over 0.51 m Lake Agassiz silty clay) recovered with a 10 cm diameter by 9 m long piston corer in 10.4 m water depth. Dated bulrush seed lies directly below Agassiz Unconformity in stiff, crumbly, calcareous silty clay. Sample elevation is based on acoustic profile and seismic reflection travel time to the Agassiz Unconformity (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This date of 4.7 ka on a bulrush (*Scirpus* sp.) seed within crumbly zone of sediment below the Agassiz Unconformity provides one of the oldest age estimates for the onset of marsh or shallow lake sedimentation in the northern South Basin of Lake Winnipeg. It is probable that the sample post-dates the Agassiz Unconformity, but was introduced into the underlying Lake Agassiz silty clay through fractures in the subaerial or shallow subaqueous surface (see BGS-1477). Preservational state of the dated bulrush seed is fair.

Lab. Number: **CAMS-46189**
Field Number: 97301-010 13 cm
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, L. Hopkinson, F. Jodrey
Collected: 1997.03.24

Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material:
Latitude: 51° 00.22' N
Longitude: 96° 52.24' W
Elevation: 217.7 m (lake level); 214.2 m (sample elevation)
Locality: off Sandy Bar, Hecla Island, northern South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 2190 ± 50 yr BP
Significance: age of shoreface deposition in northern South Basin
Assoc. Dates: CAMS-44529 1850 ± 50 yr BP
References: Forbes, D.L., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-12
Analyst: A.M. Telka

Stratigraphy: 0.74 m sediment recovered from 1.18 m hammer core, 10 cm in diameter, taken through ice in 3.4 m water depth. Dated bulrush seed is from within a 52 cm thick unit of ripple-laminated, calcareous, silty sand, approximately 41 cm above erosional contact representing the Agassiz Unconformity, which is underlain by firm silty clay.

Comments (D.L. Forbes & A.M. Telka): This sample dates shoreface deposition as described for CAMS-44529. The older age of this sample, 37 cm higher in the core than CAMS-44529, indicates that organics in this facies were reworked by storm waves and currents and were presumably derived from shoreline deposits nearby. Preservational state of the dated bulrush (*Scirpus* sp.) seed is poor (no basal filaments attached, seed tip worn showing signs of mechanical abrasion). Macrofossil seeds and insect fossil remains, representing mostly shoreline indicators with a few aquatic taxa, are fragmented with very few complete.

Lab. Number: **CAMS-46190**
Field Number: 96900 LW 217PC 135-140 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS Namao
Collected: 1996.08.28
Material: two bulrush seeds
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: noncalcareous silty clay
Latitude: 51° 08.0' N
Longitude: 96° 35.1' W
Elevation: 218.1 m (lake level); 205.7 m (sample elevation)
Locality: between Black and Hecla Islands, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 3340 ± 40 yr BP
Significance: age of upper unconformity
Assoc. Dates: CAMS-35498 3340 ± 50 yr BP; CAMS-46191 3910 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Forbes, D.L. et al., this volume; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-34
Analyst: A.M. Telka

Stratigraphy: 3.10 m lake sediment recovered with a 10 cm diameter by 9 m long piston corer in 11.1 m water depth. Dated bulrush seeds are from crumbly silty clay directly below upper sharp contact, and are 1.62 m above a lower erosional unconformity at 3.02 m down-core, interpreted as the Agassiz Unconformity. This second contact is underlain by stiff, calcareous, silty clay. Sample elevation is based on acoustic profile and seismic reflection travel time to the lower unconformity (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This date gives an age of 3.3 ka for infill sediments below the upper of two unconformities on the Hecla-Black Sill. With CAMS-35498, it fixes the age of this unconformity, correlative with the main Agassiz Unconformity, which truncates a local depression (possible channel) cut into the older sediments prior to 3.9 ka (CAMS-46191). Preservational state of the two bulrush seeds is good with remnants of the basal filaments and style tip intact. Macrofossils within this sample are not as diverse in comparison to the other two samples dated from this core. Plant macrofossils include mostly single seeds of shoreline taxa (*Rumex*, *Chenopodium*, *Potentilla*, Verbena and Compositae) and aquatic arrowhead (*Sagittaria*). Mostly aquatic sponges (*Spongilla* type) and immature forms of midges (Chironomidae) and mayflies (Ephemeroptera) represent faunal fossil remains.

Lab. Number: **CAMS-46191**
Field Number: 96900 LW 217PC 253-257 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.28
Material: six goosefoot seeds
Taxon Dated: *Chenopodium* spp. identified by A.M. Telka
Encl. Material: noncalcareous silty clay
Latitude: 51° 08.0' N
Longitude: 96° 35.1' W
Elevation: 218.1 m (lake level); 204.6 m (sample elevation)
Locality: between Black and Hecla Islands, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 3910 ± 60 yr BP
Significance: age of lower unconformity
Assoc. Dates: CAMS-35498 3340 ± 50 yr BP; CAMS-46190 3340 ± 40 yr BP
References: Todd et al., 1996; Vance & Telka, 1998 Forbes, D.L. et al., this volume; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-35
Analyst: A.M. Telka

Stratigraphy: 3.10 m lake sediment recovered with a 10 cm diameter by 9 m long piston corer in 11.1 m water depth. Dated goosefoot seeds are from crumbly silty clay below a sharp upper contact at 1.32 m down-core. The seeds are 0.45 m above a lower erosional unconformity at 3.02 m down-core, interpreted as the Agassiz Unconformity. This second contact is underlain by stiff, calcareous, silty clay. Sample elevation is based on acoustic profile and seismic reflection travel time to the lower unconformity (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This date gives a minimum age of 3.9 ka for the lower of two erosional contacts at this location on the Hecla-Black Sill. This lower contact is the base of a shallow depression (possible channel) and is filled with partially bedded crumbly silty clay, truncated at the upper contact at 3.3 ka (CAMS-35498 and CAMS-46190). Preservational state of the dated goosefoot seeds is excellent. Plant and insect fossil remains from this interval are well preserved and diverse. The dated goosefoot seeds comprise two species and are the most abundant macrofossil within this sample. Plant macrofossils include a few aquatics such as cat-tail (*Typha* sp.), pondweed (*Potamogeton* sp.) and naiad (*Najas flexilis*) but are predominantly represented by shoreline types of sedges (Cyperaceae including many *Scirpus*), buckwheat family (Polygonaceae), cinquefoil (*Potentilla* spp.), vervain (*Verbena*) and water-starwort (*Callitriche*). Insect fossils include aquatic types such as water boatmen (Corixidae), predaceous diving beetles (Dytiscidae), and water scavenger beetles (Hydrophilidae). Terrestrial insect types include leaf beetles (Chrysomelidae) and ground beetles (Carabidae). The combined plant and insect macrofossil evidence suggests a shoreline close to the core site at 3.9 ka.

Lab. Number: **CAMS-46192**
Field Number: 96900 LW 224PC 584-589 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.09.03
Material: bulrush seed
Taxon Dated: *Scirpus* sp. identified by A.M. Telka
Encl. Material: highly calcareous sand
Latitude: 50° 33.0' N
Longitude: 96° 47.2' W

Elevation: 217.9 m (lake level); 202.85 m (sample elevation)
Locality: approximately 10 km from southern shoreline, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 5350 ± 50 yr BP
Significance: age of submerged shoreline
Assoc. Dates: CAMS-35496 3550 ± 70 yr BP; CAMS-35501 3570 ± 120 yr BP;
CAMS-35615 4090 ± 60 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-38
Analyst: A.M. Telka

Stratigraphy: 7.31 m Lake Winnipeg sediment (5.50 m clay and silty clay over 0.32 m interlaminated mud and sand over 1.49 m sand) recovered with a 10 cm diameter by 9 m long piston corer in 8.5 m water depth. Dated bulrush seed is from the top of the lower sand unit (a fine to medium calcareous sand including some coarse sand with mud clasts and mollusc shells), directly below a sharp contact overlain by interlaminated organic-rich silt-clay mud and sand. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of calcareous sand unit (Lewis et al., this volume).

Comments (A.M. Telka & C.F.M. Lewis): Preservational state of the dated bulrush seed is poor (outer surface showing signs of mechanical abrasion). This age estimate of 5.3 ka is the oldest date obtained from the South Basin. Based on younger dates from this core, including younger shell age of 4.0 ka (CAMS-35615) lower in the sand, and the poor preservational state of the dated bulrush seed, this sample is believed to be reworked. The dated seed may represent an episode of earlier seasonal ponding in the South Basin.

Lab. Number: **CAMS-46193**
Field Number: 96900 LW 220PC 395-400 cm below top of cored sediment
Submitter(s): L.H. Thorleifson, C.F.M. Lewis
Collector(s): GSC & MGSB scientists on CCGS *Namao*
Collected: 1996.08.29
Material: water-smartweed seed
Taxon Dated: *Polygonum amphibium* L. identified by A.M. Telka
Encl. Material: noncalcareous silty clay mud
Latitude: 50° 56.8' N
Longitude: 96° 40.9' W
Elevation: 217.8 m (lake level); 202.7 m (sample elevation)
Locality: Pearson Reef, approximately 5 km off Hecla Island, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:
$\delta^{13}C$: -25 ‰
Normalized Age: 3870 ± 140 yr BP
Significance: age estimate for the onset of mud sedimentation over relict shore zone at Pearson Reef
Assoc. Dates: CAMS-32193 4760 ± 70 yr BP; CAMS-35495 3920 ± 70 yr BP;
CAMS-35494 1970 ± 170 yr BP; CAMS-35500 2940 ± 80 yr BP
References: Todd et al., 1996; Vance & Telka, 1998; Forbes, D.L. et al., this volume; Lewis, C.F.M. et al., this volume; Telka, A.M., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-36
Analyst: A.M. Telka

Stratigraphy: 5.53 m Lake Winnipeg sediment (4.07 m clay and silty clay mud with occasional sand interbeds over 1.46 m sand and gravel) recovered with a 10 cm diameter by 9 m long piston corer in 10.5 m water depth. Dated water-smartweed seed is from near the base of noncalcareous silty clay mud 7 to 12 cm above sharp contact underlain by fine calcareous sand with granules and occasional medium sand and pebbly gravel. Sample elevation is based on acoustic profile and seismic reflection travel time to the top of sand (Lewis et al., this volume).

Comments (D.L. Forbes & A.M. Telka): This date provides an age estimate of 3.9 ka for flooding of the former shore zone at Pearson Reef under rising lake levels and the beginning of mud deposition over the sand. Preservational state of the dated water-smartweed (*Polygonum amphibium* L.) seed is excellent.

Lab. Number: **CAMS-46194**
Field Number: 97301-014 4-6 cm
Submitter(s): D.L. Forbes
Collector(s): D.L. Forbes, F. Jodrey
Collected: 1997.03.25
Material: 22 beggar-tick seeds
Taxon Dated: *Bidens* sp. identified by A.M. Telka
Encl. Material: muddy peat
Latitude: 50° 44.07' N
Longitude: 96° 32.90' W
Elevation: 217.6 m (lake level); 213.1 m (sample elevation)
Locality: off Elk Island, South Basin, Lake Winnipeg
Uncorrected Age:
δ^{13}C: -25 ‰
Normalized Age: 1420 ± 60 yr BP
Significance: age for top of peat in 4.4 m present water depth, lake-level change in Lake Winnipeg
Assoc. Dates: CAMS-44531 1800 ± 60 yr BP; GSC-1977 1660 ± 60 yr BP;
GSC-1980 1060 ± 210 yr BP
References: Forbes, D.L., this volume
Assoc. Taxa: See Plant and Insect Macrofossil Report MFRPT 98-19
Analyst: A.M. Telka

Stratigraphy: 0.87 m sediment recovered from 1.26 m hammer core, 10 cm in diameter, taken through ice in 4.4 m water depth. Dated beggar-tick seeds are from muddy peat between two contacts at 0.03 and 0.10 m downcore, underlain by 41 cm thick unit of laminated woody peat with clay-rich laminae over sharp erosional contact representing the Agassiz Unconformity at 0.51 m down-core.

Comments (A.M. Telka & D.L. Forbes): This date of 1.4 ka provides a maximum age for the top of peat that began accumulating at this site about 1.8 ka (see CAMS-44531). Preservational state of the dated beggar-tick seeds is excellent. Plant macrofossil assemblage from this dated interval is typical of a shoreline environment with abundant sedges (*Carex* spp.), smartweed (*Polygonum lapathifolium*), dated beggar-ticks (*Bidens* sp.) and a few aquatic emergents of cat-tail (*Typha* sp.). Insect fossils are minimally represented and include mostly rove beetles (Staphylinidae), a family with varied habitats but often seen in decaying material and/or along shorelines. This date, which suggests lake levels at least 4.5 m below present, is bracketed by the top and bottom ages obtained for the nearby (or coextensive) peat deposit represented by GSC-1977 and GSC-1980. It therefore suggests more rapid lake-level change (31 cm/century) than inferred from GSC-1980.

Lab. Number: **GSC-1977**
Field Number: Lk. Winnipeg-1973-1 (bottom)
Submitter(s): F. Penner
Collector(s): A. Swedlo
Collected: 1973
Material: peat
Taxon Dated:
Encl. Material:
Latitude: 50° 44' N
Longitude: 96° 33' W
Elevation: ~217 m (lake level); ~214 m (sample elevation)
Locality: Elk Island, 3.2 km north of Victoria Beach, Lake Winnipeg, Manitoba
Uncorrected Age: 1660 ± 60 yr BP
δ^{13}C:
Normalized Age:
Significance: lake level change in Lake Winnipeg
Assoc. Dates: GSC-1980 1060 ± 210 yr BP
References: Lowdon & Blake, 1979; Penner & Swedlo, 1974.

Stratigraphy: Shelby tube sample from borehole through sandy barrier (tombolo) connecting Elk Island with the mainland. Dated upper 10 cm from 40 cm thick peat with willow (*Salix* sp.), sedge (Cyperaceae) and bulrush (*Scirpus* sp.), identified by J. Stewart, underlain by clay and overlain by wind- and water-sorted sand and gravel barrier up to 5 m thick.

Comments (F. Penner): The peat is approximately 3 m below the long-term mean lake level and suggests that because of differential uplift between the northern end of Lake Winnipeg and the southern end, the lake level at this site has risen by about 3 m in 1060 years.

Lab. Number:	**GSC-1980**
Field Number:	Lk. Winnipeg-1973-1 (top)
Submitter(s):	F. Penner
Collector(s):	A. Swedlo
Collected:	1973
Material:	peat
Taxon Dated:	
Encl. Material:	
Latitude:	50° 44' N
Longitude:	96° 33' W
Elevation:	~217 m (lake level); ~214 m (sample elevation)
Locality:	Elk Island, 3.2 km north of Victoria Beach, Lake Winnipeg, Manitoba
Uncorrected Age:	1060 ± 210 yr BP
$\delta^{13}C$:	
Normalized Age:	
Significance:	lake level change in Lake Winnipeg
Assoc. Dates:	GSC-1977 1660 ± 60 yr BP
References:	Lowdon & Blake, 1979; Penner & Swedlo, 1974.

Stratigraphy: Shelby tube sample from borehole through sandy barrier (tombolo) connecting Elk Island with the mainland. Dated upper 10 cm from 40 cm thick peat with willow (*Salix* sp.), sedge (Cyperaceae) and bulrush (*Scirpus* sp.), identified by J. Stewart, underlain by clay and overlain by wind- and water-sorted sand and gravel barrier up to 5 m thick.

Comments (F. Penner): The peat is approximately 3 m below the long-term mean lake level and suggests that because of differential uplift between the northern end of Lake Winnipeg and the southern end, the lake level at this site has risen by about 3 m in 1060 years.

Lab. Number:	**GSC-3281**
Field Number:	E.N.-1979-3
Submitter(s):	E. Nielsen
Collector(s):	W.H. Rand
Collected:	1941
Material:	freshwater shells
Taxon Dated:	*Strophitus undulatus* identified by E. Nielsen
Encl. Material:	
Latitude:	50° 40' N
Longitude:	96° 35' W
Elevation:	217 m (lake level)
Locality:	Traverse Bay, South Basin, Lake Winnipeg, Manitoba
Uncorrected Age:	570 ± 100 yr BP
$\delta^{13}C$:	-7.9 ‰
Normalized Age:	840 ± 100 yr BP
Significance:	hard-water effect (reservoir error)
Assoc. Dates:	BGS-1946 775 ± 105 yr BP; BGS-1947 545 ± 80
References:	Blake, 1982.; Nielsen et al., 1982.
Analyst:	E. Nielsen

Stratigraphy: Surface collection of modern shells on beach.

Comments (E. Nielsen & W. Blake, Jr.): The sample was dated to determine the error due to recycled old carbon in radiocarbon dates on freshwater shells from the area of Winnipeg River which is underlain by highly calcareous sediments. The date suggest that radiocarbon dates on freshwater molluscs of greater antiquity from this area could be several hundred years too old. Caution must be used in applying the apparent age of this pelecypod sample to other species of freshwater molluscs collected at other sites. The aragonitic paired valves comprising this sample were whole and the periostracum was intact except in the hinge area. The inside of the shells was characterized by pearly lustre.

Lab. Number:	**GSC-5258**
Field Number:	NB-90-2(c)
Submitter(s):	E. Nielsen
Collector(s):	E. Nielsen
Collected:	1990.06.25
Material:	wood
Taxon Dated:	*Ulmus americana* identified by H. Jetté (GSC Wood Rpt. No. 91-41)
Encl. Material:	silty clay
Latitude:	50° 24' 10" N
Longitude:	96° 51' 55" W
Elevation:	217 m (lake level)
Locality:	4 km west of the main channel of the Red River on the south shore of Lake Winnipeg, Manitoba
Uncorrected Age:	20 ± 60 yr BP
δ^{13}C:	-25.9 ‰
Normalized Age:	10 ± 60 yr BP (modern)
Significance:	dendrochronology of south central Manitoba
Assoc. Dates:	
References:	McNeely & Atkinson, 1996.

Comment (E. Nielsen): Samples GSC-5258, -5264, and -5269 were collected from the south shore of Lake Winnipeg as part of a wider effort to construct a dendrochronology for south central Manitoba. The logs were lying in the water or on the shore having been pushed up by winter shore ice. None of the samples was found in any significant stratigraphic context. The logs were selected from hundreds of driftwood samples solely on the basis that they "looked old". The subfossil oak samples (*Quercus macrocarpa*) are being crossdated with modern oak trees and logs from historic buildings in Winnipeg to anchor the chronology in A.D. 1990.

Lab. Number:	**GSC-5264**
Field Number:	NB-90-8
Submitter(s):	E. Nielsen
Collector(s):	E. Nielsen
Collected:	1990.10.25
Material:	wood
Taxon Dated:	*Larix* identified by H. Jetté (GSC Wood Rpt. No. 91-45)
Encl. Material:	sand and clay
Latitude:	50° 26' 50" N
Longitude:	96° 34' 35" W
Elevation:	217 m (lake level)
Locality:	Beaconia Beach, southeast shore of Lake Winnipeg, Manitoba
Uncorrected Age:	610 ± 50 yr BP
δ^{13}C:	-26.2 ‰
Normalized Age:	590 ± 50 yr BP
Significance:	dendrochronology of south central Manitoba
Assoc. Dates:	
References:	McNeely & Atkinson, 1996.

Comment (E. Nielsen): Samples GSC-5258, -5264, and -5269 were collected from the south shore of Lake Winnipeg as part of a wider effort to construct a dendrochronology for south central Manitoba. The logs were lying in the water or on the shore having been pushed up by winter shore ice. None of the samples was found in any significant stratigraphic context. The logs were selected from hundreds of driftwood samples solely on the basis that they "looked old". The subfossil oak samples (*Quercus macrocarpa*) are being crossdated with modern oak trees and logs from historic buildings in Winnipeg to anchor the chronology in A.D. 1990.

Lab. Number:	**GSC-5269**
Field Number:	NB-90-5
Submitter(s):	E. Nielsen
Collector(s):	E. Nielsen
Collected:	1990.10.25
Material:	wood
Taxon Dated:	*Salix* identified by H. Jetté (GSC Wood Rpt. No. 91-48)
Encl. Material:	sand
Latitude:	50° 26' 10" N
Longitude:	96° 35' 20" W
Elevation:	217.4 m (lake level)
Locality:	Patricia Beach on the southeast shore of Lake Winnipeg, Manitoba
Uncorrected Age:	90 ± 50 yr BP
$\delta^{13}C$:	-27.6 ‰
Normalized Age:	50 ± 50 yr BP (modern)
Significance:	dendochronology of south central Manitoba
Assoc. Dates:	
References:	McNeely & Atkinson, 1996.

Comment (E. Nielsen): Samples GSC-5258, -5264, and -5269 were collected from the south shore of Lake Winnipeg as part of a wider effort to construct a dendrochronology for south central Manitoba. The logs were lying in the water or on the shore having been pushed up by winter shore ice. None of the samples was found in any significant stratigraphic context. The logs were selected from hundreds of driftwood samples solely on the basis that they "looked old". The subfossil oak samples (*Quercus macrocarpa*) are being crossdated with modern oak trees and logs from historic buildings in Winnipeg to anchor the chronology in A.D. 1990.

Appendix 10.7

Grain-size data for CCGS *Namao* 96900 cores and yawl 96900 grabs

D.L. Forbes

Geological Survey of Canada (Atlantic)

ORGANISATION OF APPENDIX

This appendix is divided into three sections as follows:

Section 1 contains a table and figures showing grain-size distributions, summary statistics, and percentages of gravel, sand, silt, and clay for 93 samples representing a range of facies in Winnipeg and Agassiz Sequence deposits sampled in 1996 gravity and piston cores from Lake Winnipeg.

Section 2 contains a table and figures showing equivalent data for 21 nearshore grab samples collected in Lake Winnipeg in 1996 by the *Namao* launch.

Section 3 presents the results of a small inter-instrument study undertaken in the laboratories of GSC-Atlantic and GSC-Ottawa (Terrain Sciences Division) to determine the differences in grain-size distributions obtained using Sedigraph, Coulter laser, and Galai laser instruments for size analysis of muds from Winnipeg and Agassiz Sequence deposits.

METHODS

The data in Sections 1 and 2 are based on analyses carried out by Donald Clattenburg and assistants in the grain-size laboratory at GSC-Atlantic, Bedford Institute of Oceanography, Dartmouth, Nova Scotia. Standard procedures for sample preparation and separation used in this laboratory are described in Syvitski et al. (1991). General methodology followed McCave and Syvitski (1991), but departed from the latter in defining the silt-clay boundary at 4 μm, after the original Wentworth (1922) size classification. Samples were pretreated using 3% hydrogen peroxide to remove digestible organics, and then disaggregated using disodium hexametaphosphate (Calgon) and ultrasonic vibration. Mud passing a 53 μm sieve was analysed by settling in a Sedigraph 5100 x-ray attenuation instrument with digital interface (Coakley and Syvitski, 1991). Sand and coarse silt were analysed by settling in the BIST-2 settling tube (Syvitski et al., 1991). Coarse materials (pebbles and granules) retained on a 2 mm sieve were analysed by standard sieve techniques at 0.25 ϕ intervals.

Moment statistics (mean, sorting [standard deviation], skewness, and kurtosis) were computed on the log-transformed size distributions, expressed in phi units where $D_\phi = -\log_2 D_{mm}$. In these units, larger positive values imply finer sediment and negative values denote very coarse sand and gravel. Median size (D_{50}) and percentages of gravel, sand, silt, and clay were determined from the size frequency distributions, where frequency is expressed as mass percent coarser. For D < 2 mm, size is the equivalent spherical settling diameter (ESSD) (McCave and Syvitski, 1991). For D greater than or equal to2 mm, size is the sieve mesh opening. The lower size limit was assumed arbitrarily at ~0.2 μm (12 ϕ), following Griffiths (1967), and the finest class limit determined was ~0.5 μm (10.9 ϕ), 50% finer than the lower limit recommended by some authorities (Hendrix and Orr, 1972; McCave and Syvitski, 1991). For the 33 core samples and 4 grabs with D_{50}>10.9 ϕ(<0.5 μm), more than 50% of the size distribution falls into the very fine clay and finer size classes beyond the range of the analytical technique.

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SECTION 1

GRAIN-SIZE DATA FOR SAMPLES FROM *NAMAO* 96-900 CORES

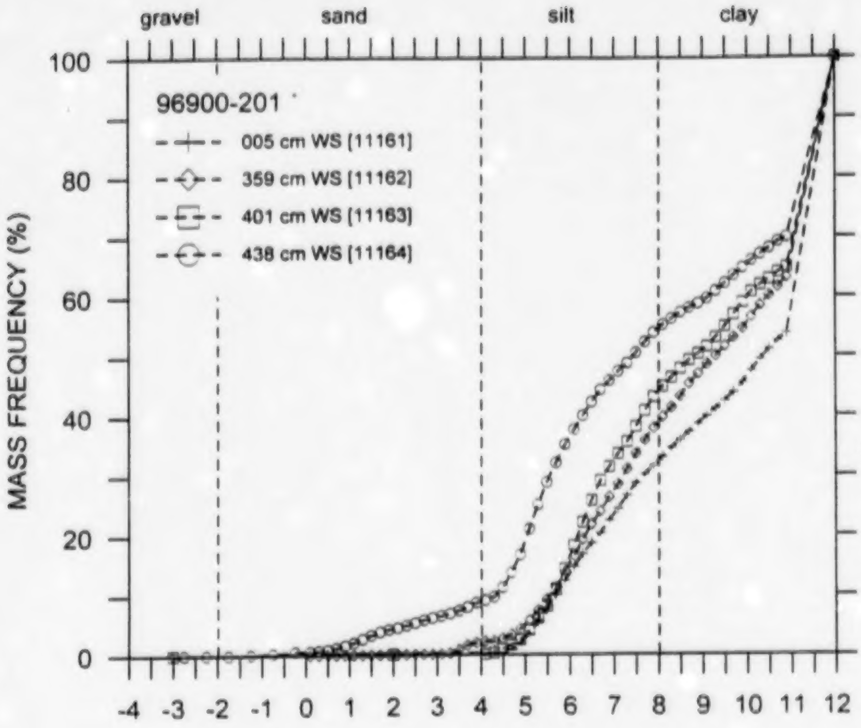
GRAIN-SIZE DATA FOR *NAMAO* 96900 CORES
settling tube + Sedigraph
(GSC-ATLANTIC)

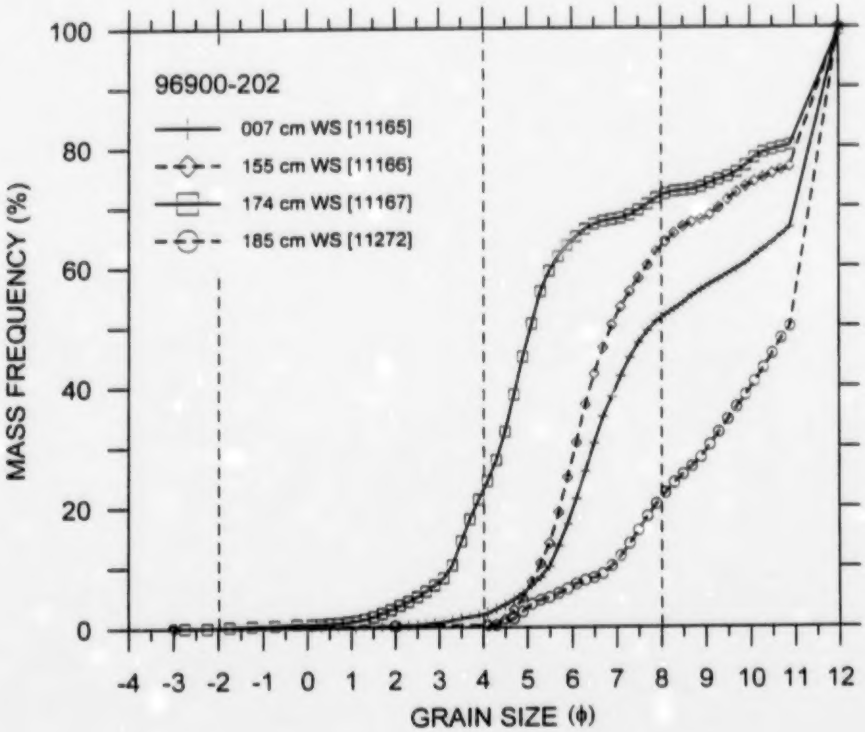
core	depth in core (m)	lab. no.	D_{50} (ϕ)	mean (ϕ)	sorting (ϕ)	skewness	kurtosis	gravel (%)	sand (%)	silt (%)	clay (%)
201GC	0.05	11161	10.36	9.66	2.55	-0.55	1.83	0.00	0.30	31.28	68.42
201PC	3.59	11162	9.30	9.20	2.60	-0.31	1.75	0.00	2.03	35.87	62.10
201PC	4.01	11163	8.84	9.02	2.58	-0.08	1.49	0.00	0.13	42.98	56.89
201PC	4.38	11164	7.44	7.99	3.30	-0.18	2.01	0.16	8.59	45.15	46.10
202GC	0.07	11165	7.80	8.69	2.74	0.01	1.60	0.00	1.92	48.93	49.14
202PC	1.55	11166	6.89	8.01	2.56	0.55	1.87	0.00	0.35	62.14	37.51
202PC	1.74	11167	5.08	6.47	3.28	0.64	2.17	0.33	21.04	50.47	28.15
202PC	1.85	11272	10.90	10.19	2.22	-0.97	2.92	0.00	0.27	20.20	79.53
203GC	0.05	11169	10.90	10.79	1.67	-1.17	3.40	0.00	0.01	9.61	90.38
203PC	2.60	11170	11.11	10.86	1.76	-1.71	5.71	0.00	0.02	8.08	91.90
203PC	5.52	11171	11.08	10.90	1.55	-1.19	3.57	0.00	0.00	6.25	93.75
204PC	3.89	11172	10.90	10.27	2.19	-1.13	3.39	0.00	1.12	15.95	82.93
204PC	5.10	11173	10.91	10.19	2.24	-1.01	2.94	0.00	0.80	18.25	80.95
204PC	5.23	11174	10.45	9.75	2.52	-0.72	2.17	0.00	1.46	25.49	73.04
204PC	5.45	11175	10.91	10.20	2.22	-0.98	2.85	0.00	0.57	19.18	80.25
205GC	0.05	11176	10.99	10.17	2.36	-0.98	2.74	0.00	0.35	21.87	77.78
205PC	0.75	11178	5.81	6.97	3.56	0.25	1.51	0.17	37.07	21.53	41.24
205PC	0.83	11179	3.75	5.78	3.62	0.58	2.48	1.97	51.43	19.10	27.50
206GC	0.05	11184	10.75	9.56	2.96	-0.98	3.01	0.16	4.87	24.99	69.98
206PC	0.40	11185	11.02	10.22	2.61	-1.67	5.58	0.10	4.69	13.00	82.21
206PC	0.69	11186	10.77	10.01	2.50	-1.18	3.45	0.00	4.85	14.37	80.78
207GC	0.05	11187	11.01	10.50	1.99	-1.07	3.00	0.00	0.10	15.16	84.74
208GC	0.05	11188	11.03	10.75	1.72	-1.29	4.04	0.00	0.01	8.56	91.43
208PC	0.96	11189	10.94	10.24	2.21	-0.98	2.87	0.00	0.31	19.34	80.34
208PC	1.27	11190	11.10	10.96	1.52	-1.34	4.00	0.00	0.01	5.94	94.05
209GC	0.05	11191	10.99	10.66	1.80	-1.46	5.54	0.00	0.63	9.35	90.02
209PC	0.47	11192	11.02	10.61	1.89	-1.26	3.81	0.00	0.04	12.49	87.46
209PC	0.98	11193	8.32	8.55	3.03	-0.09	1.53	0.00	1.93	46.14	51.93
209PC	1.20	11194	11.04	10.73	1.84	-1.60	5.38	0.00	0.00	8.34	91.66
212GC	0.05	11195	10.26	9.42	2.82	-0.69	2.20	0.07	4.08	27.99	67.86
213GC	0.05	11196	9.98	9.56	2.45	-0.71	2.57	0.00	1.05	27.17	71.78
214GC	0.05	11197	10.04	9.42	2.76	-0.64	2.39	0.11	2.18	32.19	65.52
214PC	1.55	11198	10.04	9.68	2.36	-0.71	2.52	0.00	0.62	25.00	74.37
214PC	3.73	11201	10.27	10.00	2.09	-0.94	3.91	0.12	0.39	18.46	81.03
214PC	3.96	11202	10.87	10.15	2.19	-0.76	2.15	0.00	0.03	22.71	77.26
215GC	0.05	11203	9.96	9.30	2.79	-0.49	1.80	0.00	2.73	32.82	64.45
215PC	2.48	11206	10.24	9.77	2.34	-0.65	2.37	0.00	0.55	26.31	73.14
215PC	3.45	11215	9.06	9.28	2.44	-0.25	1.92	0.00	0.52	38.40	61.08
215PC	3.46	11216	9.75	9.67	2.33	-0.55	2.41	0.00	0.69	28.69	70.62
215PC	3.74	11217	11.07	10.67	1.86	-1.26	4.08	0.00	0.30	11.10	88.60
215PC	4.58	11218	10.91	10.11	2.23	-0.83	2.65	0.00	0.28	21.71	78.00
216GC	0.03	11219	8.04	7.53	3.98	-0.26	1.53	0.22	31.58	17.10	51.10
216GC	0.08	11220	10.55	10.00	2.23	-0.84	3.13	0.00	1.17	21.19	77.64
216PC	1.40	11221	10.95	10.39	1.96	-0.86	2.59	0.00	0.03	16.10	83.87
216PC	1.92	11222	10.95	10.42	1.90	-0.77	2.36	0.00	0.07	15.15	84.78
216PC	1.96	11223	10.18	9.79	2.30	-0.45	1.74	0.00	0.03	29.17	70.79
216PC	2.10	11224	10.91	10.36	1.89	-0.65	2.03	0.00	0.01	16.11	83.88
216PC	3.80	11225	10.92	10.26	2.10	-0.86	2.49	0.00	0.00	19.70	80.30
217GC	0.05	11226	10.93	10.02	2.39	-0.83	2.44	0.00	0.43	24.67	74.90
217GC	1.05	11227	8.23	8.62	2.89	0.00	1.37	0.00	1.04	46.46	52.50
217PC	1.27	11228	9.08	8.61	3.25	-0.40	1.81	0.00	8.78	34.81	56.42

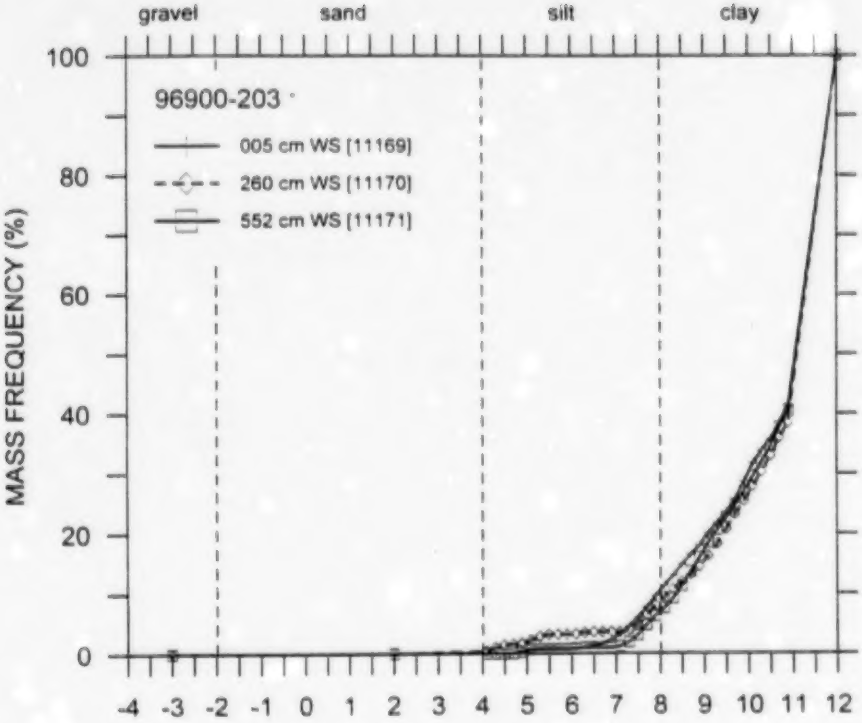
GRAIN-SIZE DATA FOR *NAMAO* 96900 CORES

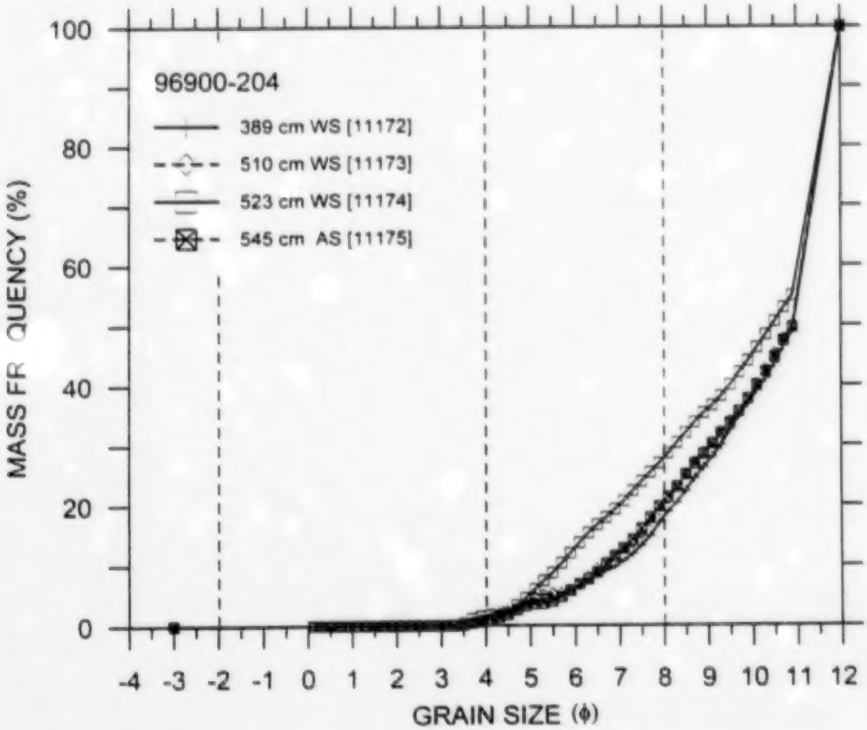
settling tube + Sedigraph
(GSC-ATLANTIC)

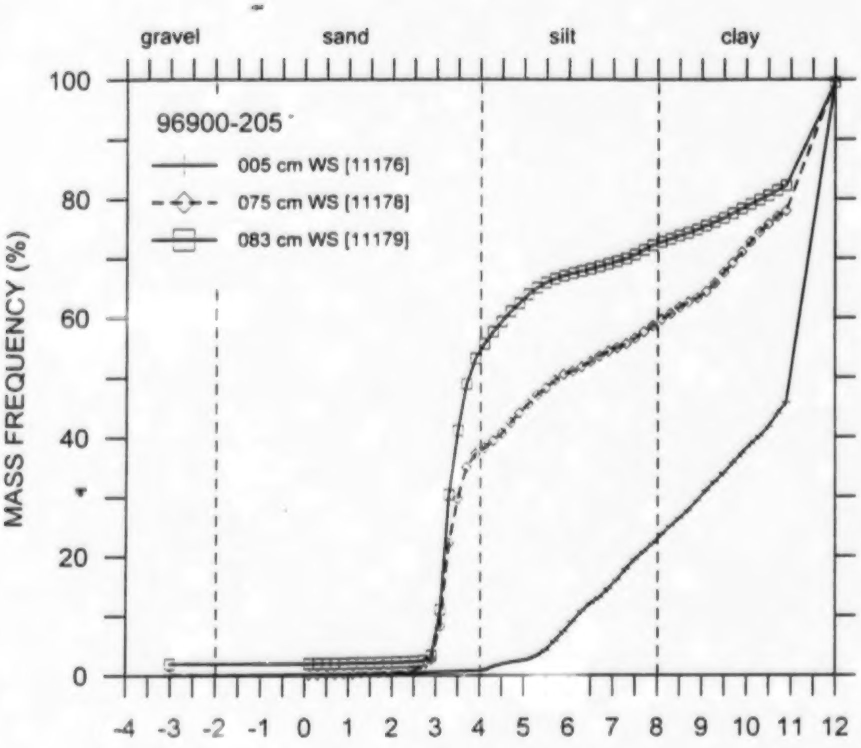
core	depth in core (m)	lab. no.	D_{50} (ϕ)	mean (ϕ)	sorting (ϕ)	skewness	kurtosis	gravel (%)	sand (%)	silt (%)	clay (%)
218PC	0.66	11229	9.99	8.81	3.73	-0.94	2.39	0.24	19.55	8.96	71.25
218PC	0.78	11230	1.83	2.13	1.55	5.13	30.69	0.00	96.72	0.66	2.62
218PC	1.05	11231	1.77	1.91	1.02	6.87	66.16	0.14	98.64	0.34	0.87
219GC	0.05	11232	11.10	10.88	1.68	-1.54	5.25	0.00	0.17	7.59	92.23
219PC	1.40	11233	10.95	10.32	2.27	-1.63	5.92	0.00	2.45	11.41	86.14
219PC	1.70	11234	2.13	2.38	1.19	6.91	52.67	0.00	98.02	0.32	1.66
219PC	2.19	11235	1.83	1.94	1.07	6.35	58.32	0.30	98.35	0.37	0.98
219PC	3.17	11236	1.91	2.15	1.38	5.75	39.34	0.01	97.69	0.33	1.97
219PC	4.16	11237	9.59	8.97	3.30	-0.80	2.30	0.00	16.92	14.37	68.71
219PC	4.39	11238	1.83	2.86	3.05	1.99	6.10	1.11	84.56	4.06	10.27
220GC	0.05	11239	11.11	10.85	1.70	-1.46	4.73	0.00	0.08	8.51	91.41
220PC	0.38	11240	11.05	10.77	1.65	-1.10	3.49	0.00	0.11	7.98	91.61
220PC	0.46	11241	2.16	2.75	2.04	3.82	16.54	0.00	93.89	1.02	5.09
220PC	2.01	11242	7.74	6.88	4.31	0.02	1.23	0.11	44.47	6.53	48.89
220PC	2.50	11243	10.97	10.48	1.90	-1.12	4.05	0.00	0.37	11.06	88.57
220PC	2.90	11244	8.49	7.80	3.88	-0.29	1.44	0.00	32.71	11.56	55.74
220PC	3.80	11245	9.77	9.43	2.78	-0.85	2.86	0.03	8.00	20.78	71.19
220PC	4.20	11246	2.13	2.76	2.08	3.78	16.11	0.00	93.81	0.93	5.26
220PC	4.65	11247	1.84	2.17	1.47	5.62	36.10	0.00	97.22	0.54	2.24
220PC	4.92	11248	1.52	1.68	3.10	2.04	7.24	13.63	77.03	1.85	7.48
220PC	5.26	11249	1.81	2.18	1.60	5.24	30.78	0.00	96.81	0.45	2.73
221GC	0.05	11250	11.12	10.83	1.84	-1.68	5.51	0.00	0.09	8.41	91.50
221PC	4.10	11251	9.73	9.75	2.23	-0.38	1.85	0.00	0.04	28.70	71.26
221PC	5.18	11252	9.23	9.45	2.40	-0.27	1.78	0.00	0.44	35.03	64.54
222GC	0.05	11253	11.12	10.88	1.67	-1.37	4.34	0.00	0.18	8.07	91.75
222PC	2.45	11254	10.76	10.39	1.84	-0.85	2.95	0.00	0.08	12.40	87.52
222PC	2.58	11255	10.64	10.08	2.15	-0.80	2.65	0.00	0.06	20.53	79.41
222PC	4.15	11256	10.45	10.03	2.09	-0.62	2.25	0.00	0.08	20.83	79.09
222PC	4.52	11257	10.77	10.26	2.00	-0.81	2.61	0.00	0.00	16.67	83.33
222PC	6.20	11258	10.80	10.16	2.16	-0.99	3.63	0.00	1.02	17.93	81.05
222PC	6.42	11259	10.35	9.91	2.20	-0.59	2.32	0.00	0.36	24.09	75.55
222PC	7.05	11260	9.49	9.61	2.31	-0.36	1.96	0.00	0.25	31.71	68.04
222PC	7.42	11261	11.08	10.63	2.00	-1.41	4.40	0.00	0.39	13.25	86.36
223GC	0.05	11262	11.15	10.98	1.59	-1.48	4.67	0.00	0.08	6.00	93.92
223PC	2.75	11263	10.97	10.45	1.94	-1.03	3.34	0.00	0.02	12.85	87.13
223PC	4.00	11264	10.98	10.55	1.78	-0.80	2.33	0.00	0.01	12.33	87.65
223PC	6.70	11265	10.01	9.46	2.62	-0.54	2.12	0.00	1.33	33.20	65.47
224GC	0.05	11266	11.09	10.73	1.81	-1.37	4.52	0.00	0.16	9.14	90.69
224PC	2.65	11267	10.93	10.40	1.90	-0.79	2.47	0.00	0.01	14.19	85.80
224PC	4.57	11268	9.55	9.44	2.48	-0.35	1.73	0.00	0.07	34.69	65.24
224PC	5.35	11269	8.79	9.15	2.53	-0.14	1.62	0.00	0.26	42.37	57.37
224PC	5.63	11270	3.04	4.81	3.32	1.39	3.26	0.00	72.53	8.02	19.45
224PC	6.90	11271	1.62	2.09	2.03	3.78	17.38	0.05	93.82	2.07	4.06

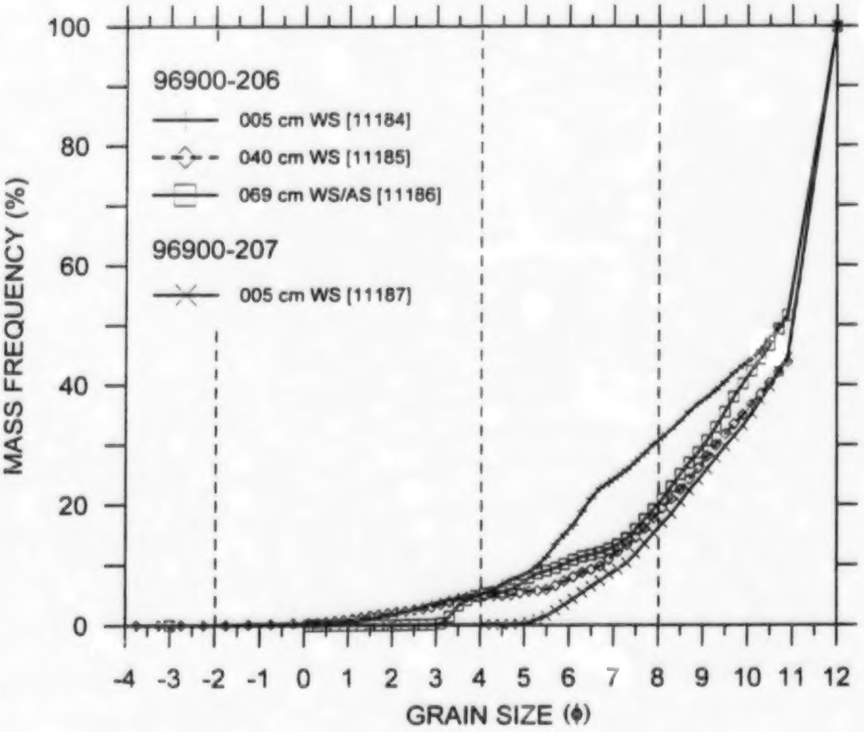

gravel
sand
silt
clay
96900-201
005 cm WS [11161]
359 cm WS [11162]
401 cm WS [11163]
438 cm WS [11164]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

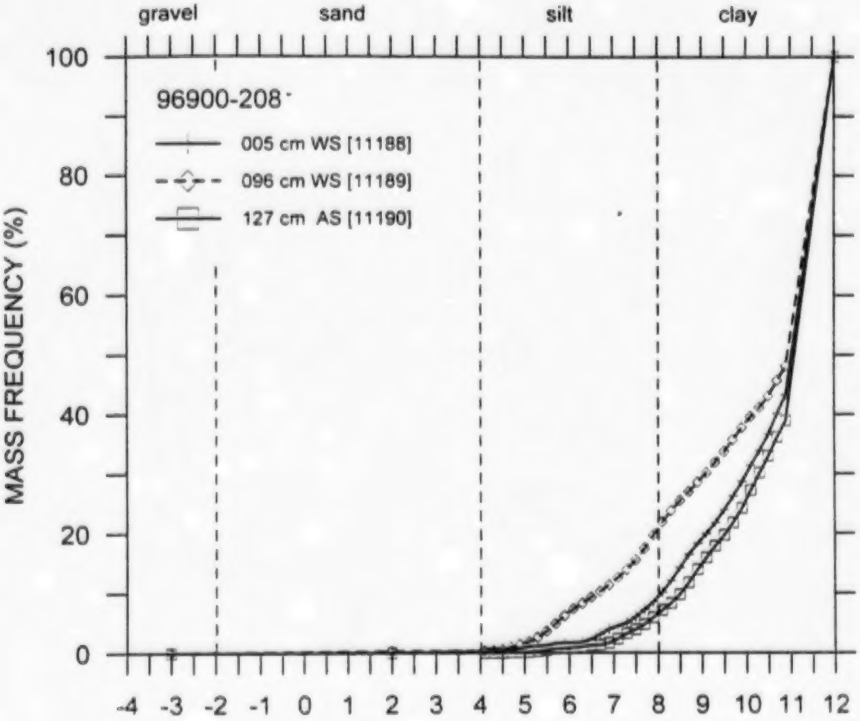

96900-202
007 cm WS [11165]
155 cm WS [11166]
174 cm WS [11167]
185 cm WS [11272]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)

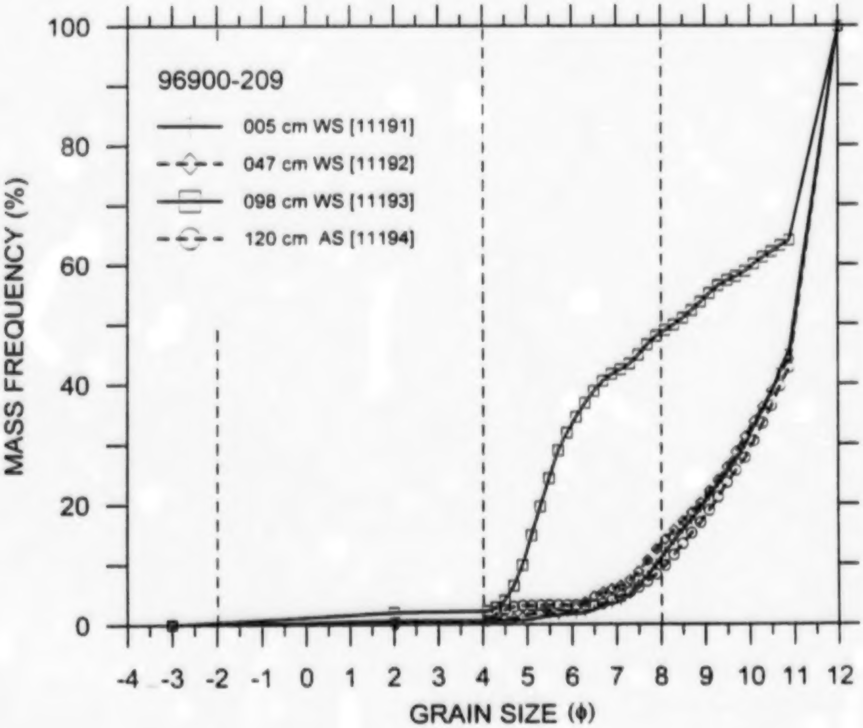

gravel
sand
silt
clay
96900-203
005 cm WS [11169]
260 cm WS [11170]
552 cm WS [11171]
MASS FREQUENCY (%)
100
80
60
40
20
0
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

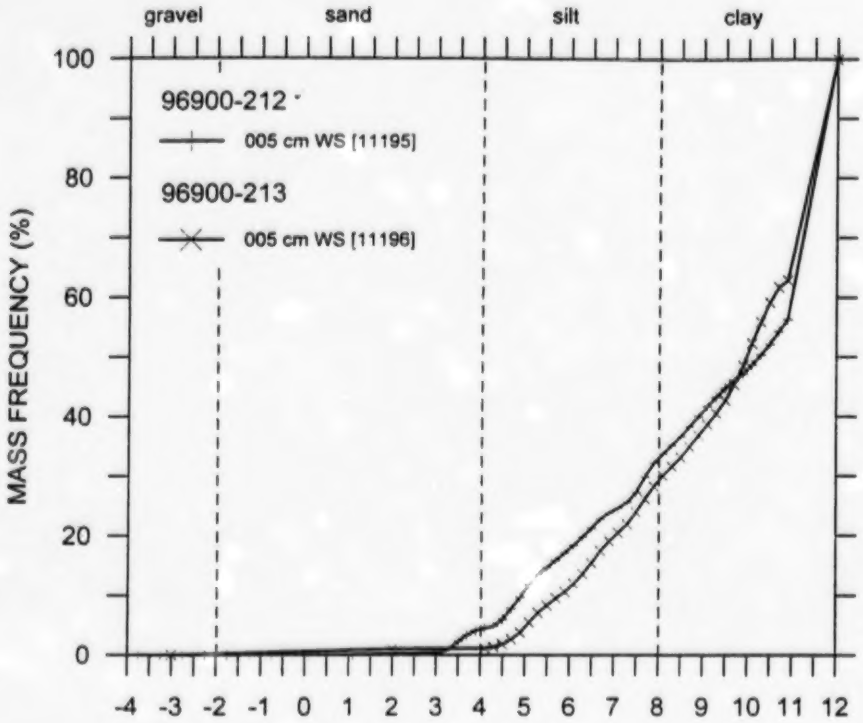

96900-204
389 cm WS [11172]
510 cm WS [11173]
523 cm WS [11174]
545 cm AS [11175]
MASS FREQUENCY (%)
100
80
60
40
20
0
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)

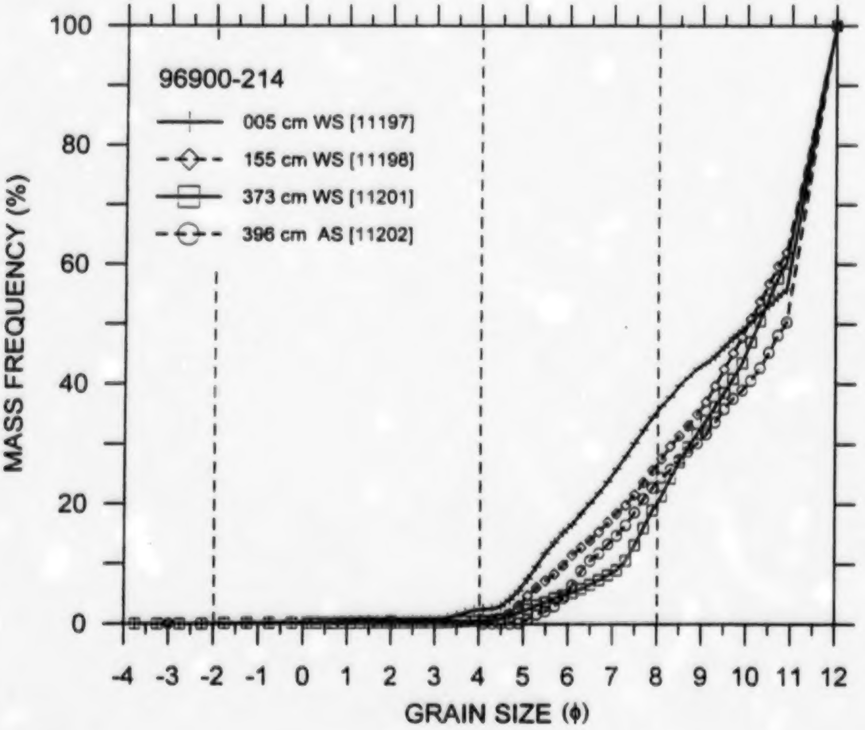

gravel
sand
silt
clay
96900-205
005 cm WS [11176]
075 cm WS [11178]
083 cm WS [11179]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

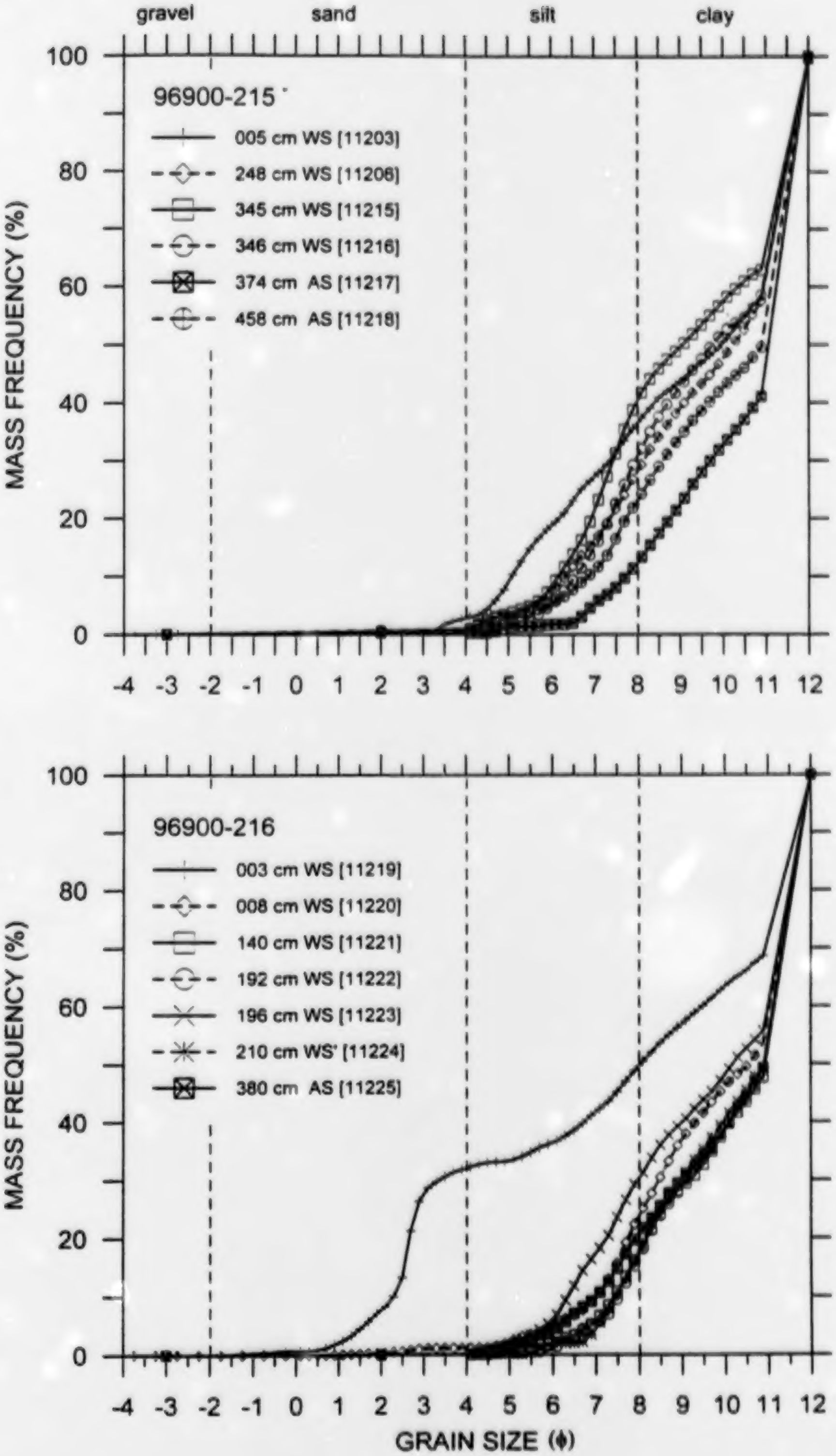

96900-206
005 cm WS [11184]
040 cm WS [11185]
069 cm WS/AS [11186]
96900-207
005 cm WS [11187]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)

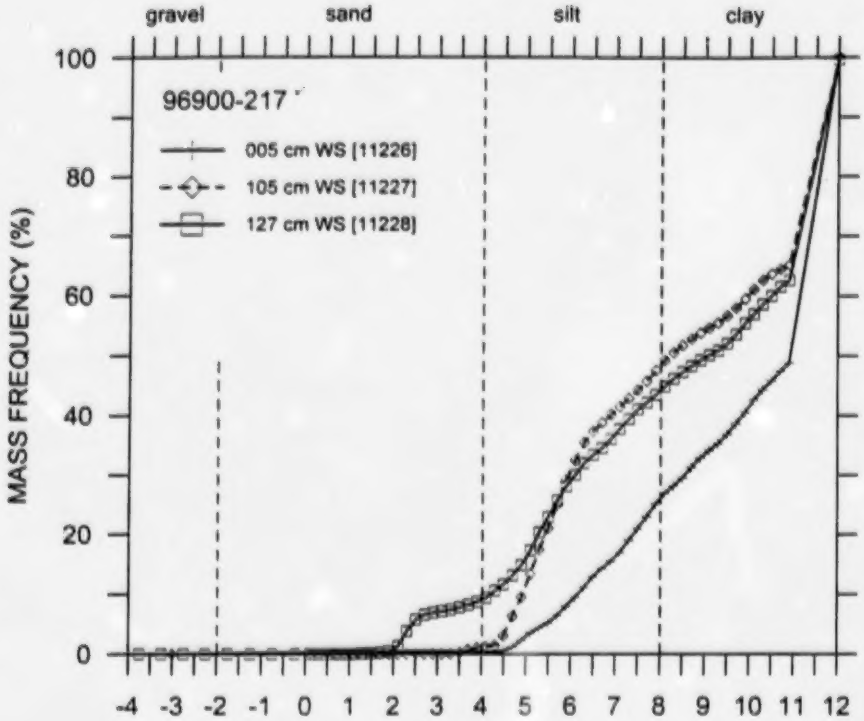

gravel
sand
silt
clay
96900-208
005 cm WS [11188]
096 cm WS [11189]
127 cm AS [11190]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

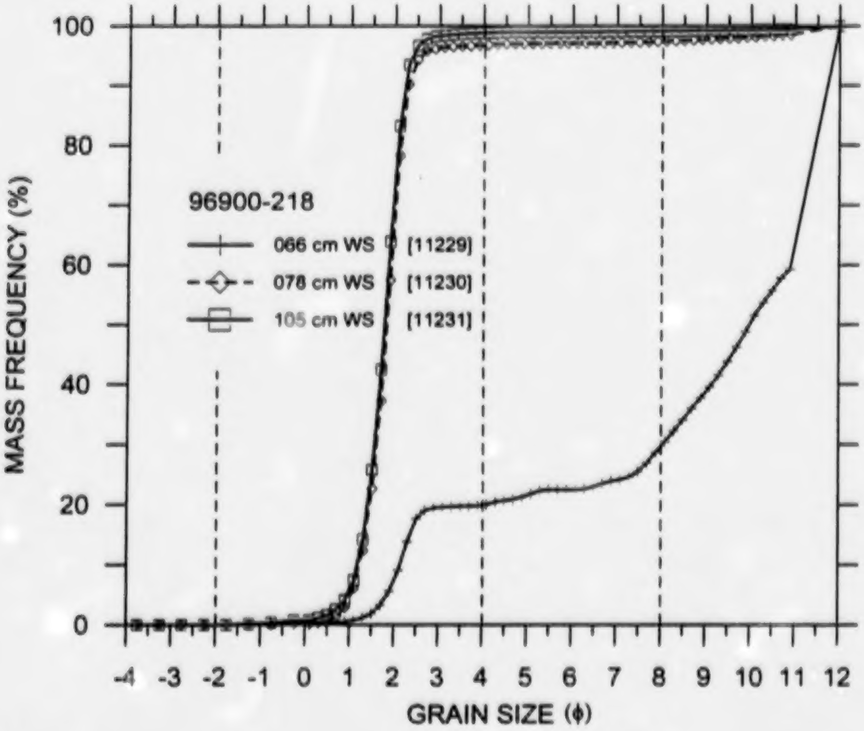

96900-209
005 cm WS [11191]
047 cm WS [11192]
098 cm WS [11193]
120 cm AS [11194]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)

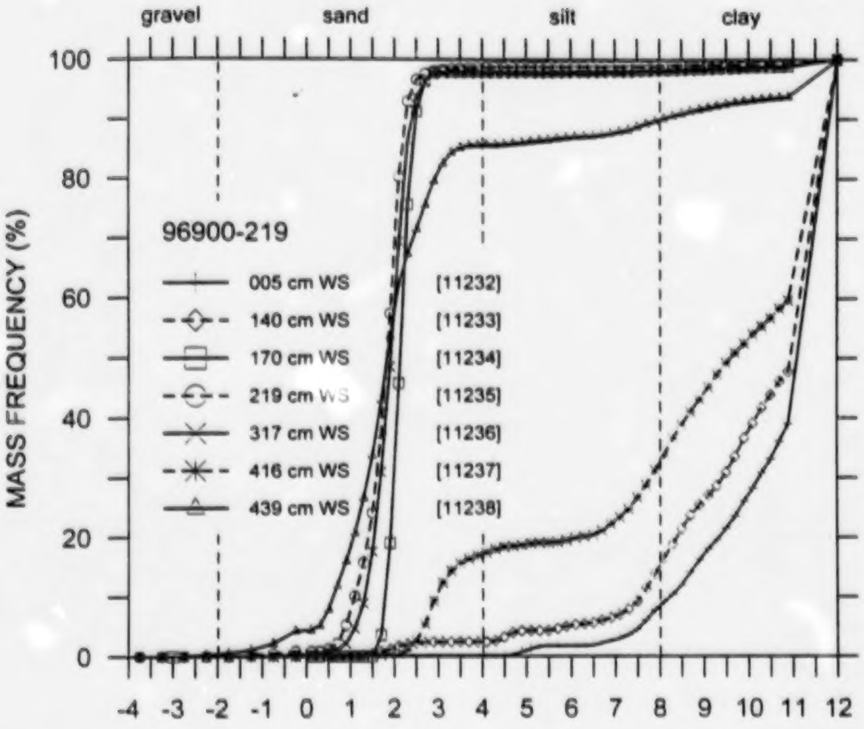

gravel
sand
silt
clay
96900-212
005 cm WS [11195]
96900-213
005 cm WS [11196]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

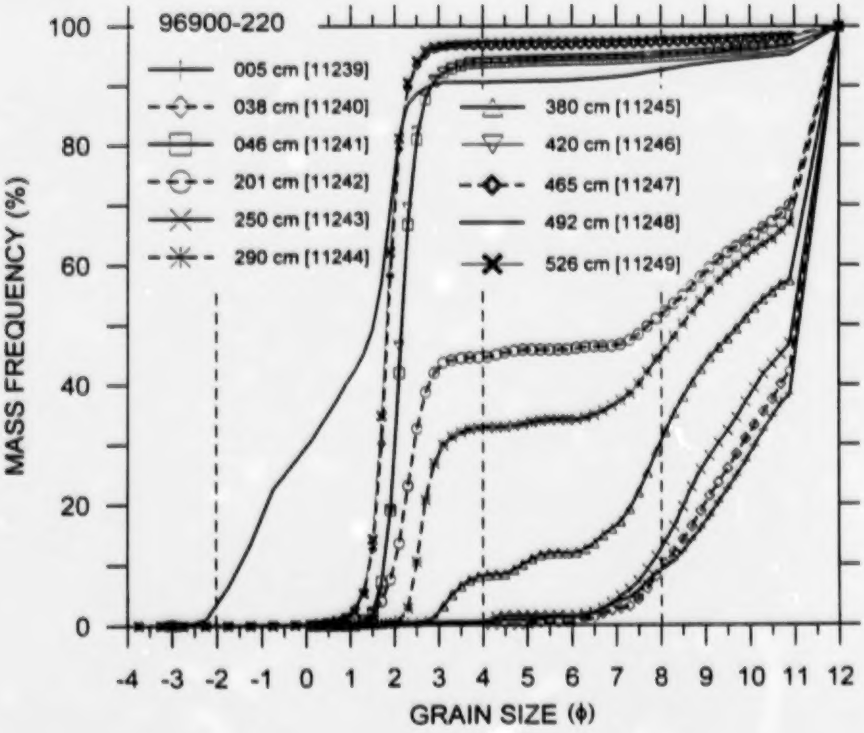

96900-214
005 cm WS [11197]
155 cm WS [11198]
373 cm WS [11201]
396 cm AS [11202]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)

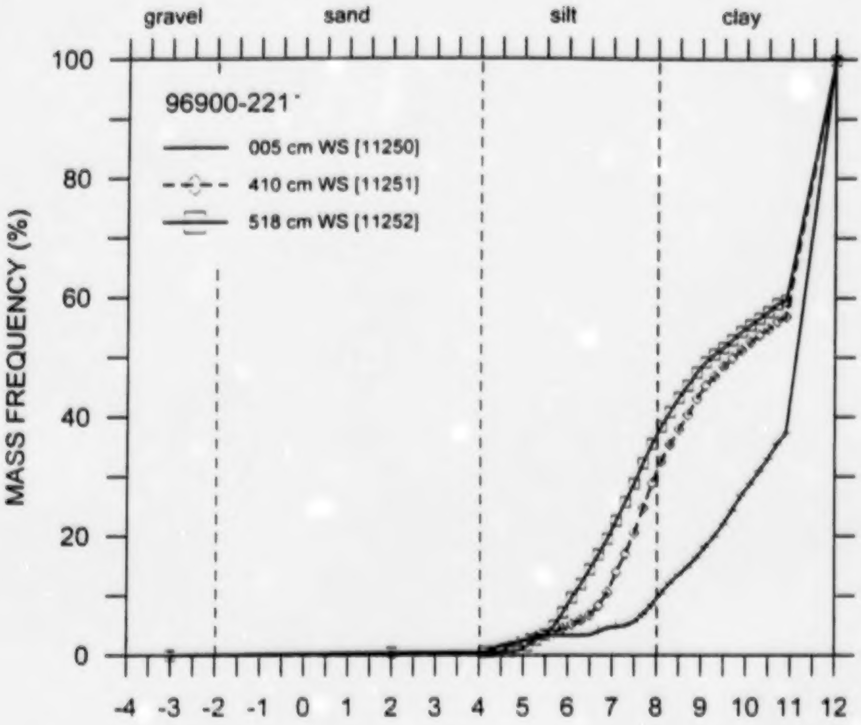

gravel
sand
silt
clay
96900-215
005 cm WS [11203]
248 cm WS [11206]
345 cm WS [11215]
346 cm WS [11216]
374 cm AS [11217]
458 cm AS [11218]
96900-216
003 cm WS [11219]
008 cm WS [11220]
140 cm WS [11221]
192 cm WS [11222]
196 cm WS [11223]
210 cm WS' [11224]
380 cm AS [11225]
MASS FREQUENCY (%)
0
20
40
60
80
100
GRAIN SIZE (ϕ)
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

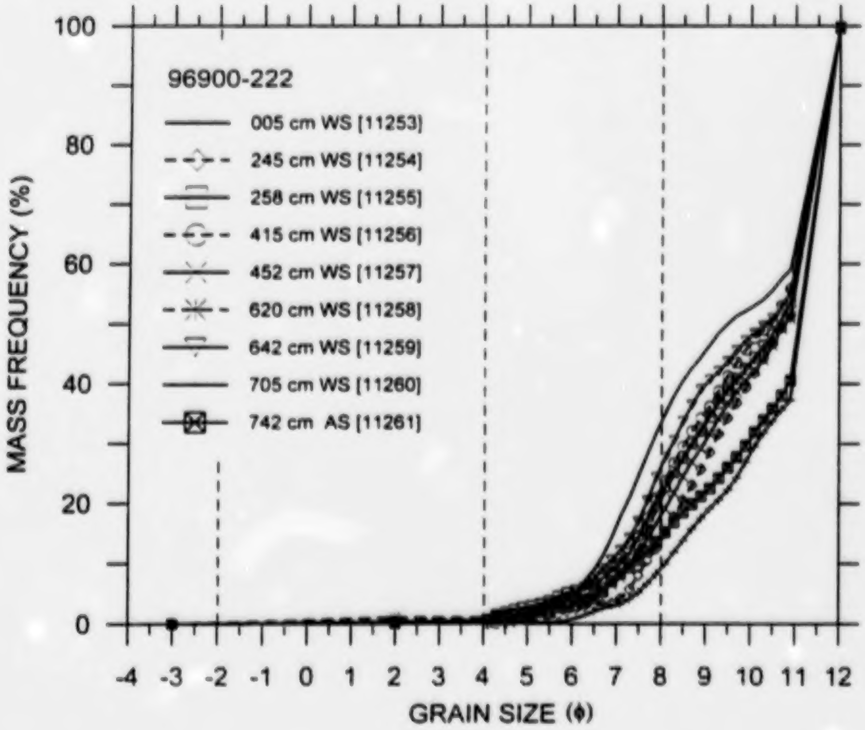

gravel
sand
silt
clay
100
80
60
40
20
0
MASS FREQUENCY (%)
96900-217
005 cm WS [11226]
105 cm WS [11227]
127 cm WS [11228]
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12

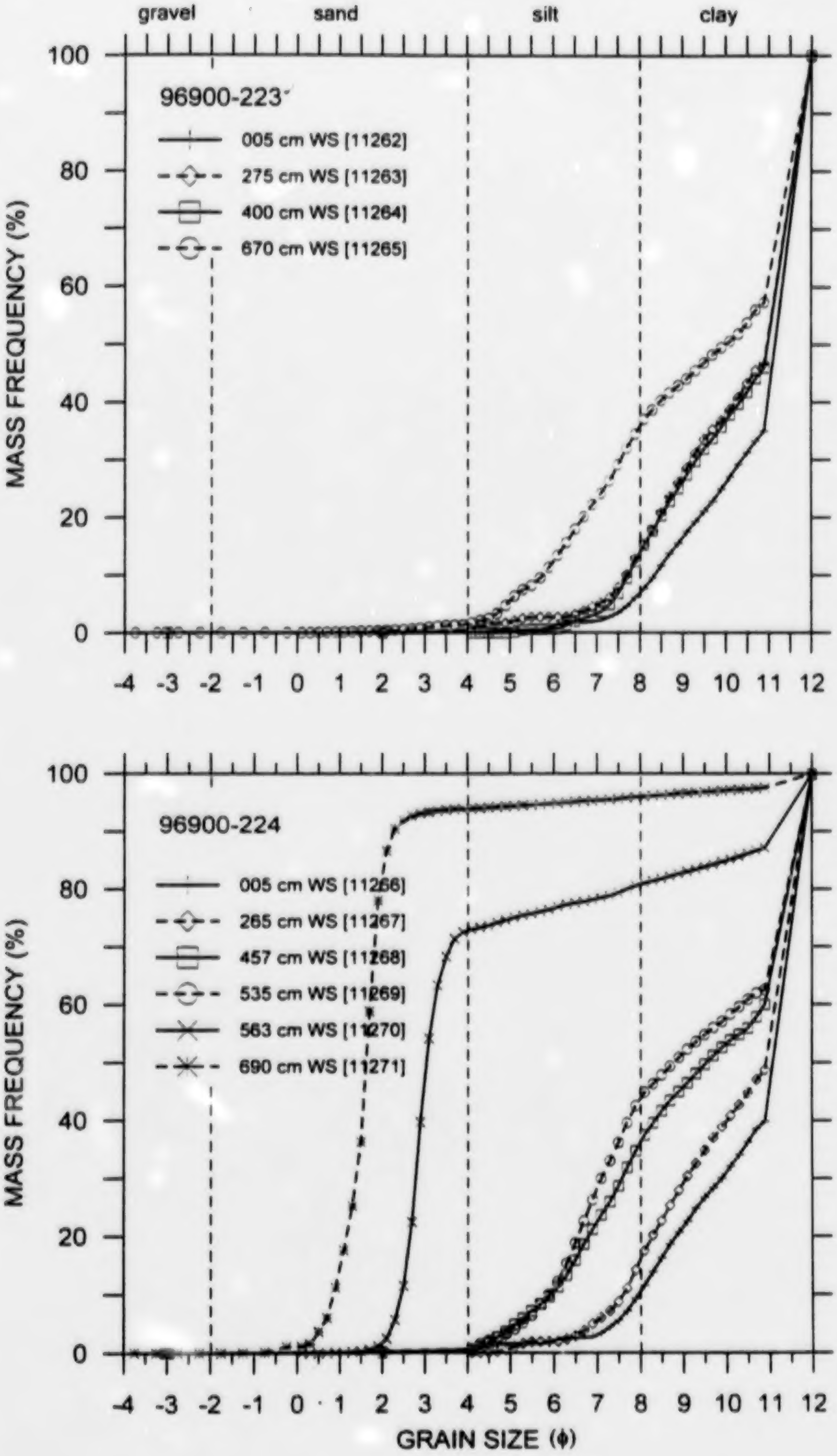

100
80
60
40
20
0
MASS FREQUENCY (%)
96900-218
066 cm WS [11229]
078 cm WS [11230]
105 cm WS [11231]
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)


gravel
sand
silt
clay
96900-219
005 cm WS [11232]
140 cm WS [11233]
170 cm WS [11234]
219 cm WS [11235]
317 cm WS [11236]
416 cm WS [11237]
439 cm WS [11238]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12


96900-220
005 cm [11239]
038 cm [11240]
046 cm [11241]
201 cm [11242]
250 cm [11243]
290 cm [11244]
380 cm [11245]
420 cm [11246]
465 cm [11247]
492 cm [11248]
526 cm [11249]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
GRAIN SIZE (ϕ)


gravel
sand
silt
clay
96900-221
005 cm WS [11250]
410 cm WS [11251]
518 cm WS [11252]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12


96900-222
005 cm WS [11253]
245 cm WS [11254]
258 cm WS [11255]
415 cm WS [11256]
452 cm WS [11257]
620 cm WS [11258]
642 cm WS [11259]
705 cm WS [11260]
742 cm AS [11261]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)

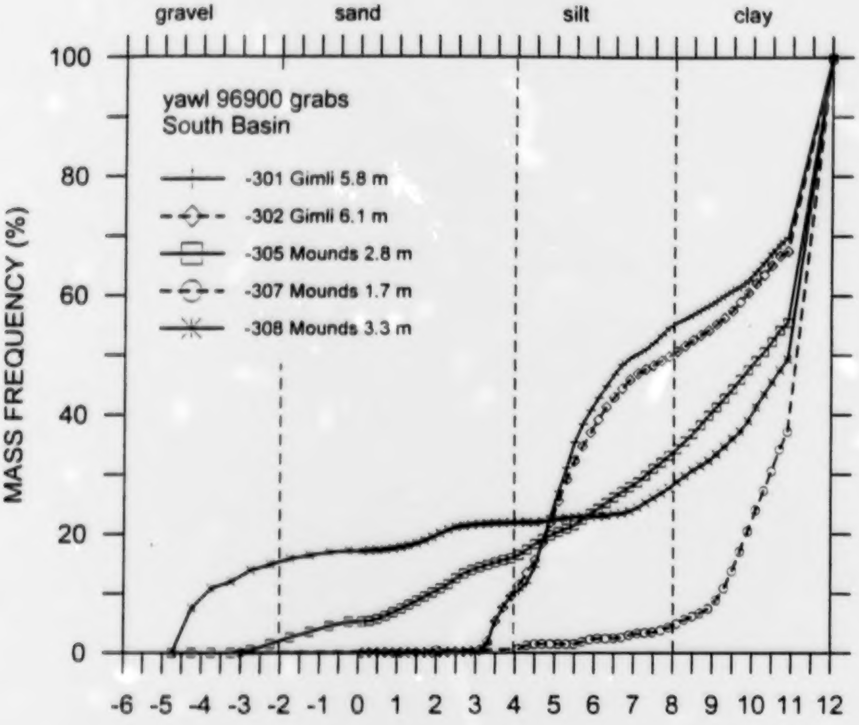

gravel
sand
silt
clay
96900-223
005 cm WS [11262]
275 cm WS [11263]
400 cm WS [11264]
670 cm WS [11265]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
96900-224
005 cm WS [11266]
265 cm WS [11267]
457 cm WS [11268]
535 cm WS [11269]
563 cm WS [11270]
690 cm WS [11271]
MASS FREQUENCY (%)
0
20
40
60
80
100
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
GRAIN SIZE (ϕ)

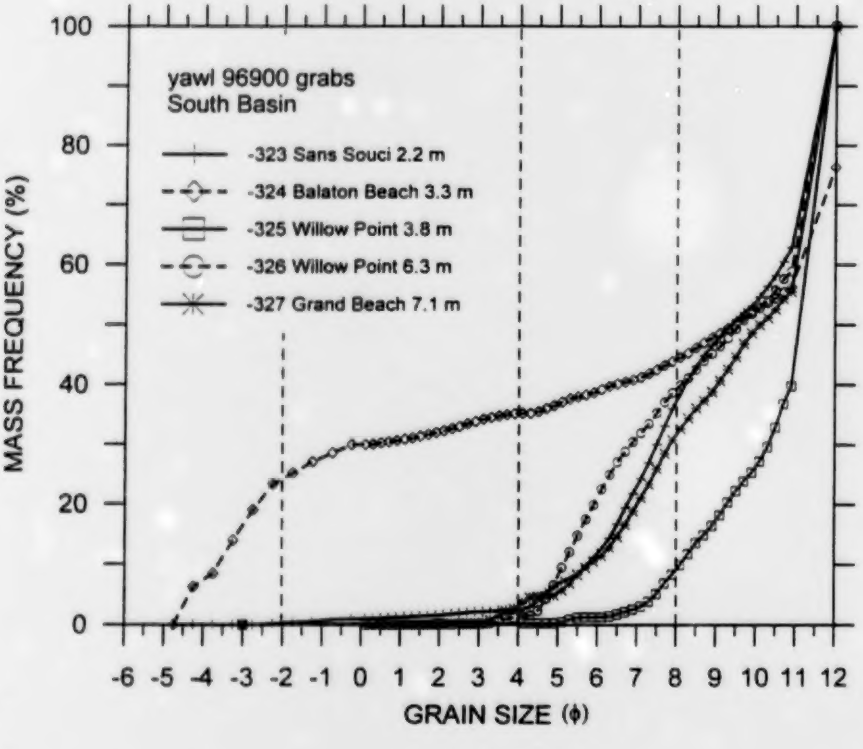
SECTION 2

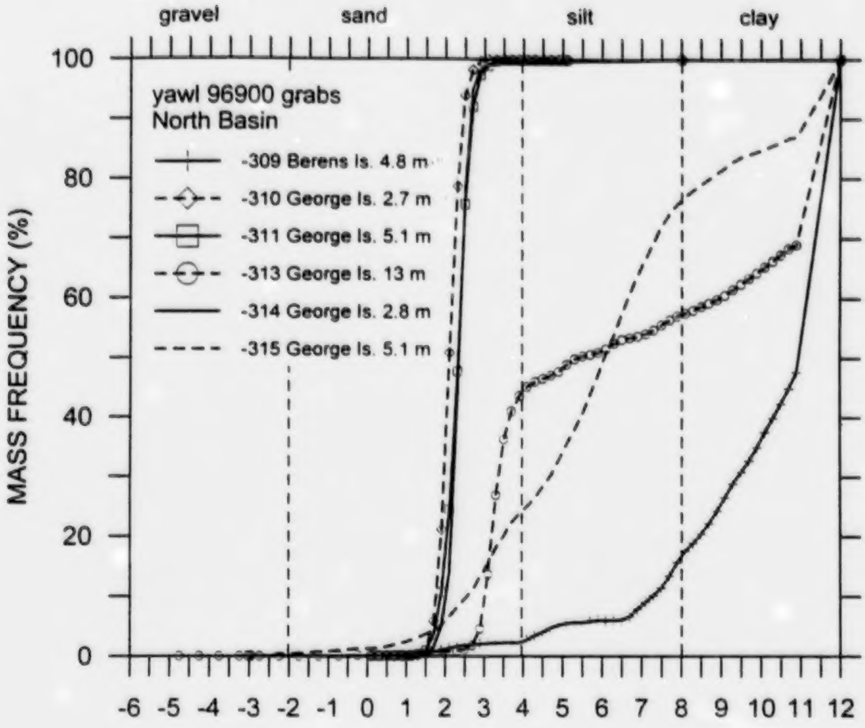
GRAIN-SIZE DATA FOR SAMPLES FROM *NAMAO* LAUNCH 96-900 NEARSHORE GRABS

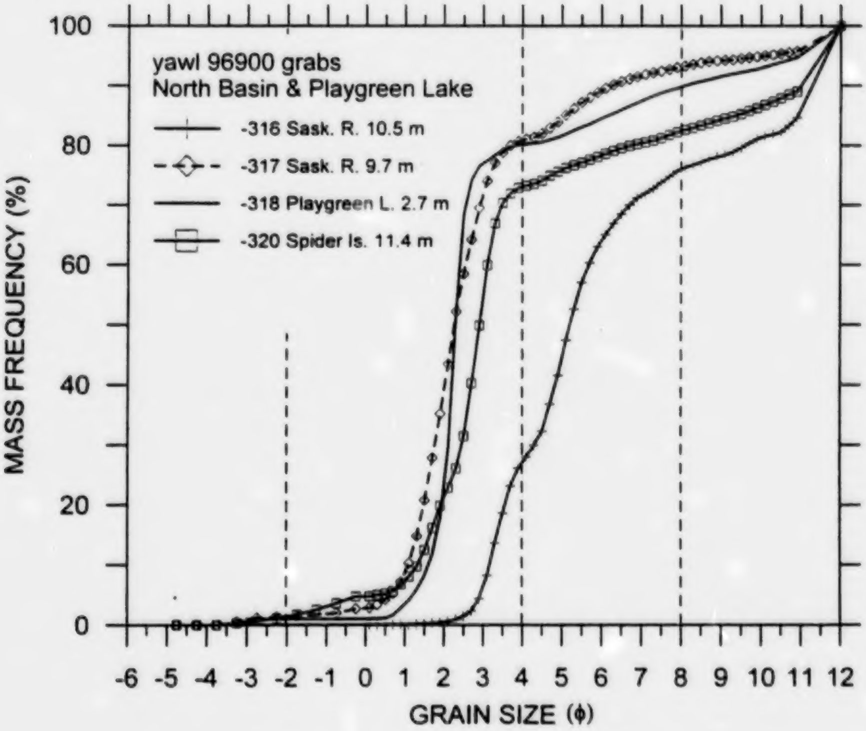
GRAIN-SIZE DATA FOR *NAMAO yawl* 96900 GRAB SAMPLES
sieve + settling tube + Sedigraph
(GSC-ATLANTIC)

sample	lab. no.	location	water depth (m)	D_{50} (ϕ)	mean (ϕ)	mean (μm)	sorting (ϕ)	skewness	kurtosis	gravel (%)	sand (%)	silt (%)	clay (%)	organic (%)
96900 -301	11019	Gimli	5.8	7.05	7.98	4.0	3.19	0.13	1.40	0.01	9.57	45.05	45.37	0.20
-304	11020	Gimli	6.1	7.89	8.18	3.4	3.21	-0.01	1.40	0.01	9.53	40.49	49.97	0.22
-305	11021	Mounds	2.8	10.21	8.68	2.4	4.09	-1.11	3.12	3.55	12.40	17.23	66.82	
-307	11022	Mounds	1.7	11.12	11.05	0.5	1.57	-2.37	10.39	0.00	0.40	3.86	95.73	
-308	11023	Mounds	3.3	10.92	8.11	3.6	5.77	-1.29	3.02	16.45	5.45	5.77	72.32	
-309	11024	Berens Is.	4.8	10.95	10.30	0.8	2.34	-1.64	5.83	0.07	2.20	13.47	84.26	
-310	11025	George Is.	2.7	2.09	2.20	218	0.32	4.91	96.16	0.00	99.92	0.08	0.00	
-311	11026	George Is.	5.1	2.32	2.40	189	0.43	3.29	75.80	0.06	99.74	0.20	0.00	
-313	11027	George Is.	13.3	5.38	7.10	7.3	3.88	0.23	1.27	0.01	43.59	14.49	42.91	0.47
-314	11028	George Is.	2.8	2.34	2.45	183	0.45	6.47	103.80	0.05	99.55	0.40	0.00	
-315	11029	George Is.	5.1	6.05	6.36	12	3.07	0.26	2.68	0.73	23.19	52.05	24.02	
-316	11030	Sask. R.	10.5	5.20	6.32	13	3.03	0.85	2.43	0.04	26.08	49.63	24.25	2.91
-317	11031	Sask. R.	9.7	2.25	3.11	116	2.68	1.79	6.74	1.69	79.03	12.38	6.91	0.71
-318	11032	Playgreen L.	2.7	2.28	3.46	91	2.89	1.78	5.61	1.03	79.07	9.52	10.39	
-319	11033	Playgreen L.	5.2	3.82	4.97	32	3.11	1.76		3.20	47.52	48.37	>mud	0.13
-320	11034	Spider Is.	11.4	2.90	4.24	53	3.57	1.12	3.31	2.54	70.31	9.34	17.81	0.71
-323	11035	Sans Souci	2.2	9.38	9.24	1.7	2.75	-0.84	3.73	0.54	1.94	33.54	63.99	
-324	11036	Balaton	3.3	5.61	4.48	45	6.43	-0.10	1.30	35.49	10.57	11.46	42.49	0.01
-325	11037	Willow Pt	3.8	11.09	10.87	0.5	1.67	-1.49	5.05	0.00	0.24	8.11	91.65	0.01
-326	11038	Willow Pt	6.3	9.60	9.19	1.7	2.79	-0.34	1.55	0.00	1.25	37.36	61.39	0.11
-327	11039	Grand Beach	7.1	10.07	9.61	1.3	2.57	-0.65	2.24	0.00	2.57	28.35	69.08	0.19


gravel
sand
silt
clay
MASS FREQUENCY (%)
0
20
40
60
80
100
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
yawl 96900 grabs
South Basin
-301 Gimli 5.8 m
-302 Gimli 6.1 m
-305 Mounds 2.8 m
-307 Mounds 1.7 m
-308 Mounds 3.3 m


MASS FREQUENCY (%)
0
20
40
60
80
100
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
GRAIN SIZE (ϕ)
yawl 96900 grabs
South Basin
-323 Sans Souci 2.2 m
-324 Balaton Beach 3.3 m
-325 Willow Point 3.8 m
-326 Willow Point 6.3 m
-327 Grand Beach 7.1 m


gravel
sand
silt
clay
yawl 96900 grabs
North Basin
-309 Berens Is. 4.8 m
-310 George Is. 2.7 m
-311 George Is. 5.1 m
-313 George Is. 13 m
-314 George Is. 2.8 m
-315 George Is. 5.1 m
MASS FREQUENCY (%)
0
20
40
60
80
100
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12


yawl 96900 grabs
North Basin & Playgreen Lake
-316 Sask. R. 10.5 m
-317 Sask. R. 9.7 m
-318 Playgreen L. 2.7 m
-320 Spider Is. 11.4 m
MASS FREQUENCY (%)
0
20
40
60
80
100
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
GRAIN SIZE (ϕ)

SECTION 3

INTER-INSTRUMENT COMPARISON FOR SUBSET OF CORE SAMPLES

Methods

This section presents the results of replicate analyses using three different instruments to determine the size distribution of Winnipeg and Agassiz Sequence muds. Four samples were taken from near the top of the Winnipeg Sequence, two in the North Basin (11165 from core 202 and 11169 from core 203) and two in the South Basin (11250 from core 221 and 11262 from core 223). Two samples were also selected representing Agassiz Sequence mud in core 215 (samples 11217 and 11218). The cores were resampled in the same intervals used for the original Sedigraph analysis (Section 1) to obtain material for analysis on two different laser instruments, a Coulter LS230 laser diffraction system with fluid module in the GSC-Atlantic laboratory (analysis by Donald Clattenburg) and a Galai Instruments 2010 PSA scanning laser system in the Terrain Sciences Division laboratory (analysis by Miriam Wygergangs under direction of Patti Lindsay). Three splits were analysed on the Coulter laser instrument and one split on the Galai PSA. The Coulter LS230 instrument uses laser diffraction spectroscopy (Agrawal et al., 1991). Particle size detection in the Galai instrument is based on time of transition theory (Last, 1996; Lindsay et al., 1998). In contrast to the Sedigraph data, where the size distribution (based on sedimentation rate using Stokes Law) is expressed in terms of mass frequency, the laser instruments generate size distributions in terms of volume frequency. Surface area and number frequency distributions can also be obtained but are not presented here.

The results of this small study demonstrate a systematic difference in the size distributions between the Sedigraph and the two laser instruments. Differences between the Coulter laser and the Galai laser were much more subtle (see cumulative size distribution plots on following pages of this Section). The following figure presents calibration plots comparing the mean size of each of the samples as determined by the Sedigraph and the Galai PSA in the upper panel and the percentage of clay (D< 4 μm) in the lower panel. It is clear from these plots and from the size distribution plots following that the Galai and Coulter laser instruments both record significantly less clay fraction than the Sedigraph. This is consistent with observations from an inter-laboratory and inter-instrument calibration experiment (Syvitski et al., 1991), which found Sedigraph data to be about 0.3 ϕ finer than narrow size standards in muds, whereas a Malvern laser diffraction instrument gave unacceptable results in the fine fractions. Similar misgivings were expressed by Agrawal et al. (1991) with respect to fine particle detection by laser diffraction instruments. The Galai 2010 PSA is reported to give better agreement with pipette analysis (Lindsay et al., 1998), but Syvitski et al. (1991) cautioned against the use of pipette as a calibration standard, given the high degree of variance in replicate analyses.

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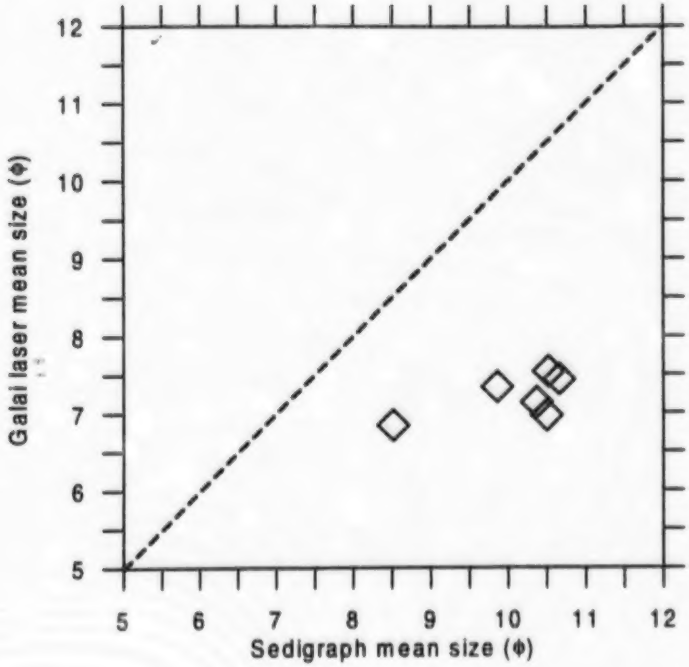
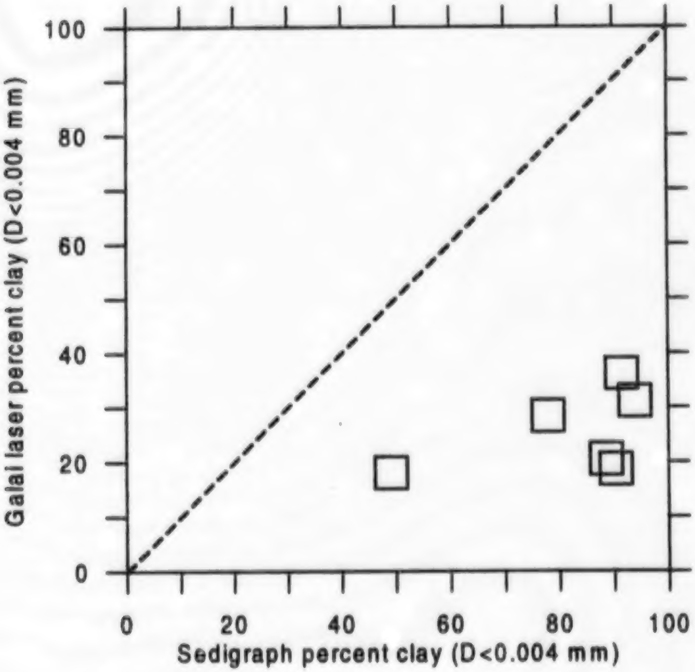
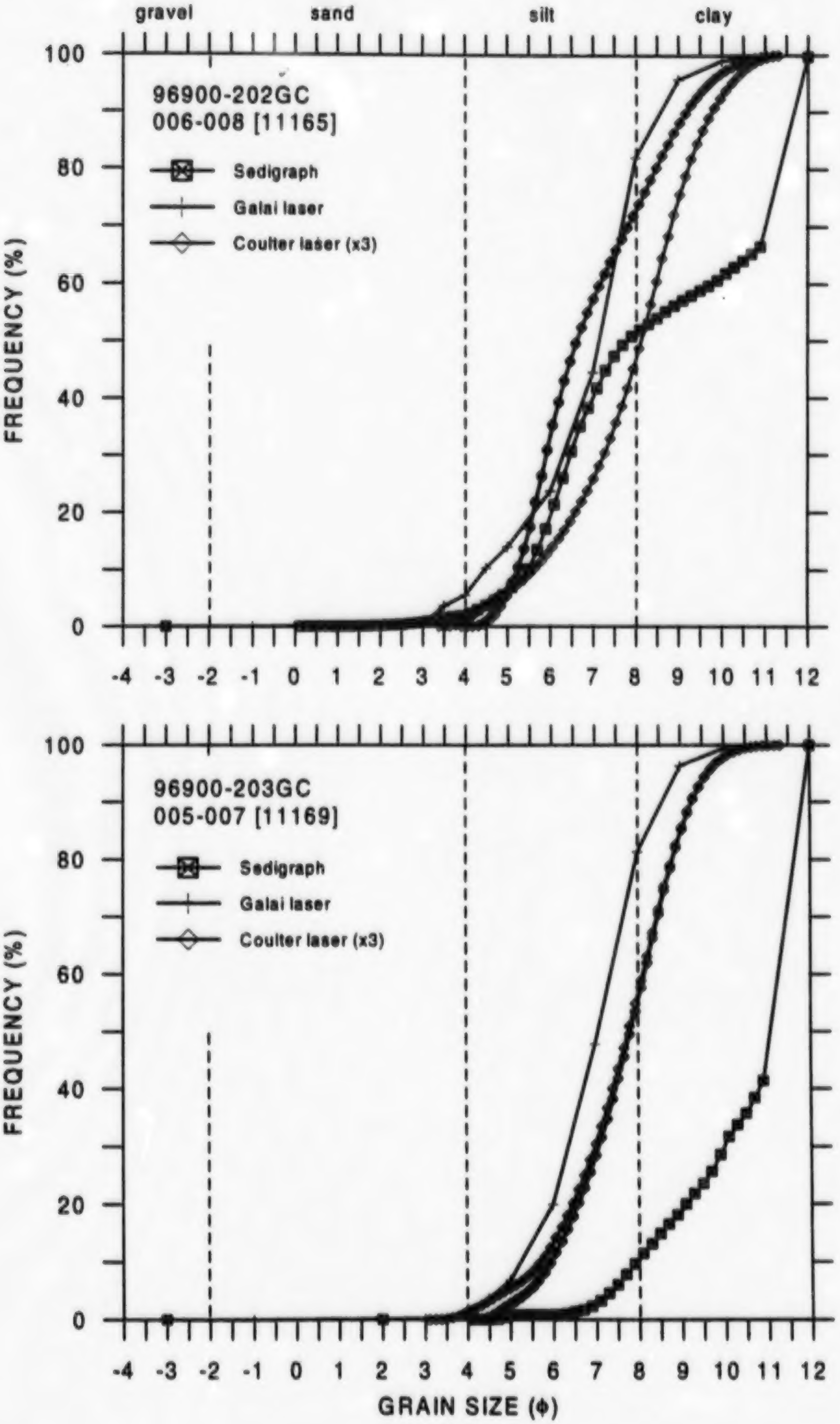

Galai laser mean size (Φ)
12
11
10
9
8
7
6
5
5
6
7
8
9
10
11
12
Sedigraph mean size (Φ)


Galai laser percent clay (D<0.004 mm)
100
80
60
40
20
0
0
20
40
60
80
100
Sedigraph percent clay (D<0.004 mm)


gravel
sand
silt
clay
96900-202GC
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Sedigraph
Galai laser
Coulter laser (x3)
FREQUENCY (%)
0
20
40
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
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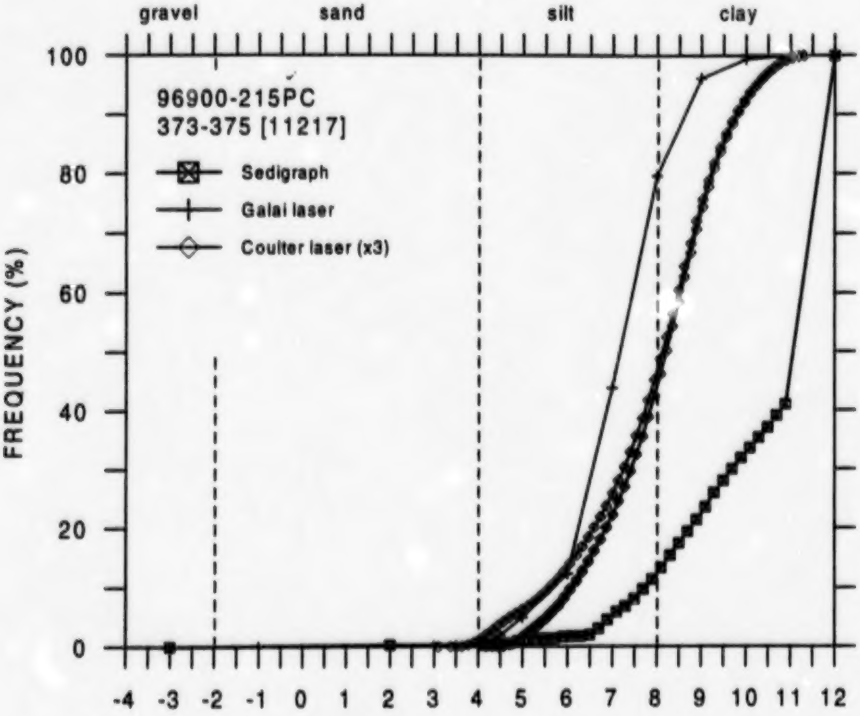
Galai laser
Coulter laser (x3)
FREQUENCY (%)
GRAIN SIZE (φ)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sand
silt
clay
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Sedigraph
Galai laser
Coulter laser (x3)
FREQUENCY (%)
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40
60
80
100
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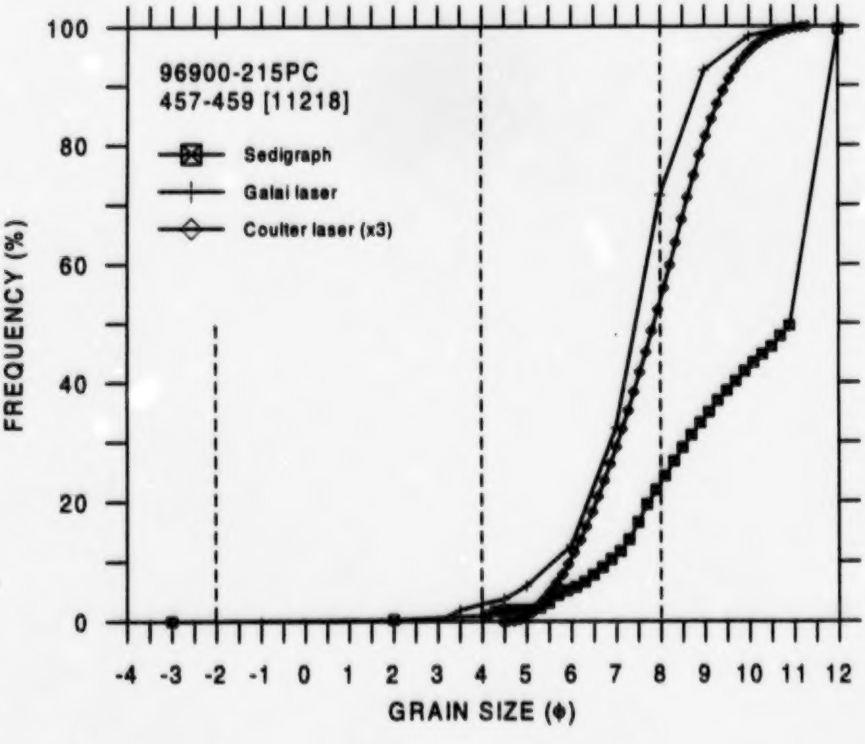
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12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Sedigraph
Galai laser
Coulter laser (x3)
FREQUENCY (%)
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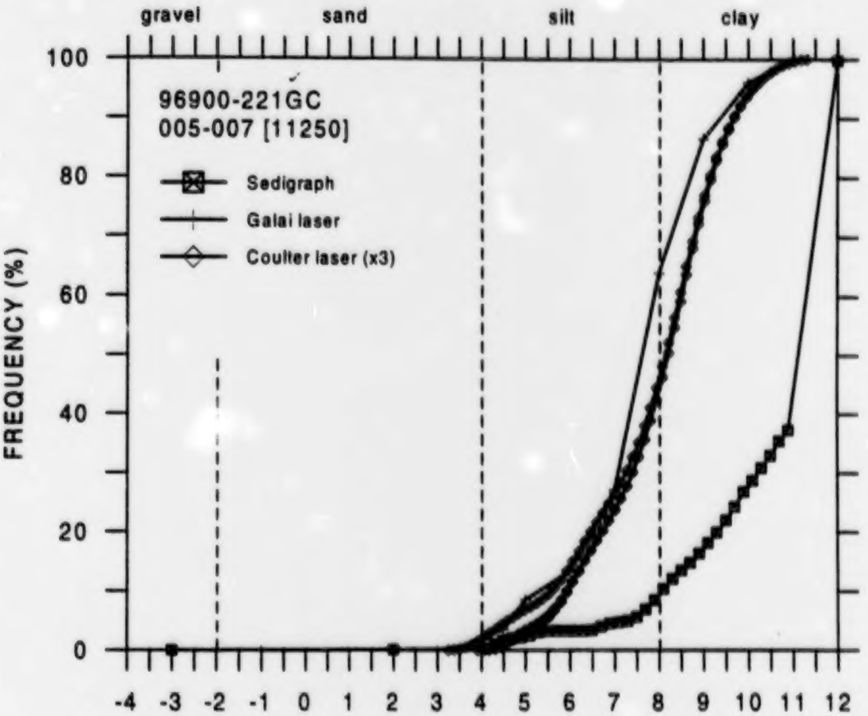
60
80
100
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (ϕ)


gravel
sand
silt
clay
96900-221GC
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Sedigraph
Galai laser
Coulter laser (x3)
FREQUENCY (%)
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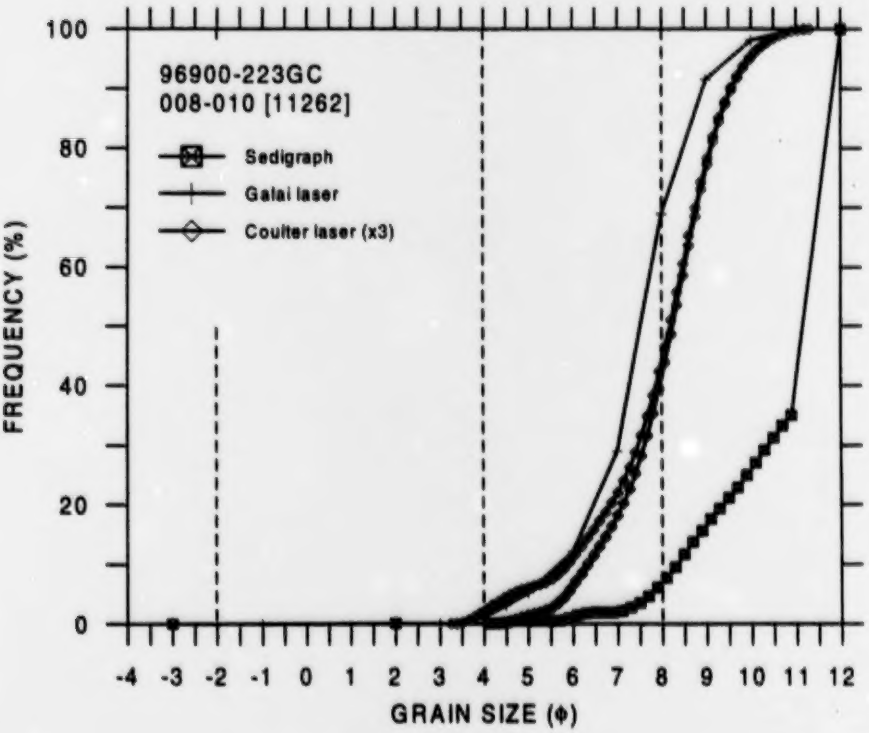
60
40
20
0
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12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Sedigraph
Galai laser
Coulter laser (x3)
FREQUENCY (%)
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80
60
40
20
0
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
GRAIN SIZE (φ)

Appendix 10.8

Texture, bulk mineralogy, geochemistry and carbon content of Lake Winnipeg sediments

P.J. Henderson

Geological Survey of Canada, Ottawa

Appendix : Texture, Bulk Mineralogy, Geochemistry and Carbon Content of Lake Winnipeg Sediments

Table 1: Texture of Lake Winnipeg Sediments

Table 2: Bulk Mineralogy of Lake Winnipeg Sediments

Table 3: Geochemistry of Lake Winnipeg Sediments

Element		Analytical Method	Detection Limit	Upper Limit
Ag	ppm	AAS	0.2	200
Al	%	ICP-AES	0.01	25.00
Ba	ppm	ICP-AES	10	10000
Be	ppm	ICP-AES	0.5	1000
Bi	ppm	ICP-AES	2	10000
Ca	%	ICP-AES	0.01	25.00
Cd	ppm	ICP-AES	0.5	500
Co	ppm	ICP-AES	1	10000
Cr	ppm	ICP-AES	1	10000
Cu	ppm	ICP-AES	1	10000
Fe	%	ICP-AES	0.01	25.00
K	%	ICP-AES	0.01	10.00
Mg	%	ICP-AES	0.01	15.00
Mn	ppm	ICP-AES	5	10000
Mo	ppm	ICP-AES	1	10000
Na	%	ICP-AES	0.01	10.00
Ni	ppm	ICP-AES	1	10000
P	ppm	ICP-AES	10	10000
Pb	ppm	AAS	2	10000
Sr	ppm	ICP-AES	1	10000
Ti	%	ICP-AES	0.01	10.00
V	ppm	ICP-AES	1	10000
W	ppm	ICP-AES	10	10000
Zn	ppm	ICP-AES	2	10000

Element		Analytical Method	Detection Limit	pper Limit
As	ppm	AAS-HYDRIDE/EDL	1	10000

Table 4: Carbon content of Lake Winnipeg Sediments

TABLE 1: Texture of Lake Winnipeg Sediments

SAMPLE			COMPLETE GRAIN SIZE DISTRIBUTION Wt %												TEXTURE					
Seq. No	Site ID	Depth (cm)	2 - 0.15 mm	0.15-0.125 mm	0.125-0.088 mm	0.088-0.063 mm	0.063-0.044 mm	0.044-0.031 mm	0.031-0.016 mm	0.016-0.008 mm	0.008-0.004 mm	0.004-0.002 mm	0.002-0.001 mm	<0.001 mm	Sand %	Silt %	Clay %	Mean um	St Dev um	Median um
1	204PC	530	0.000	0.00	0.00	2.05	0.84	3.87	7.46	14.64	30.08	22.85	13.40	4.80	2.05	56.89	41.05	9.47	13.00	4.71
2	204PC	550	0.000	0.00	0.00	0.00	0.00	0.00	3.70	12.34	30.81	25.39	19.27	8.49	0.00	46.85	53.15	4.96	4.55	3.76
3	204PC	570	0.000	0.00	0.00	0.00	0.00	1.84	13.27	13.59	29.05	22.73	14.07	5.45	0.00	57.75	42.25	7.59	7.76	4.68
4	205PC	15	0.000	0.00	0.00	0.00	0.00	3.34	15.30	16.75	30.72	18.78	10.91	4.21	0.00	66.11	33.90	9.00	0.75	5.49
5	205PC	35	0.000	0.00	0.00	0.00	3.75	5.59	13.06	16.50	30.49	18.87	8.86	2.87	0.00	69.39	30.60	11.31	12.27	6.04
6	205PC	55	0.000	0.00	0.00	0.00	5.69	4.07	11.53	12.31	29.03	20.65	12.21	4.32	0.00	62.63	37.38	10.88	13.71	5.12
7	205PC	75	0.044	1.03	10.13	10.39	15.07	19.66	22.96	8.96	6.08	3.33	1.65	0.75	21.56	72.72	5.73	41.21	29.60	35.61
8	205PC	95	0.000	0.00	4.55	6.41	5.28	3.50	9.37	11.73	27.20	17.77	10.19	3.99	10.96	57.08	31.95	18.76	26.15	5.97
9	205PC	115	0.000	0.00	5.42	7.39	3.83	5.70	11.51	16.05	25.33	14.54	7.17	3.05	12.81	62.42	24.76	22.18	29.69	7.97
10	205PC	135	0.000	0.00	0.00	0.00	0.00	4.56	7.93	14.10	33.26	21.90	12.80	5.45	0.00	59.85	40.15	7.85	0.93	4.72
11	205PC	155	0.000	0.00	0.00	0.00	3.52	2.74	5.66	17.16	32.46	21.19	11.91	5.36	0.00	61.54	38.46	8.84	11.50	4.88
12	205PC	175	0.000	0.00	0.00	0.00	0.00	0.00	6.58	13.01	31.41	25.55	16.04	7.43	0.00	51.00	49.02	5.70	5.50	4.07
13	205PC	195	0.000	0.00	0.00	0.00	3.49	2.79	7.09	14.30	31.51	22.56	12.77	5.49	0.00	59.18	40.82	8.73	11.00	4.70
14	205PC	215	0.000	0.00	0.00	0.00	0.00	2.64	5.14	10.02	31.37	25.67	17.41	7.74	0.00	49.17	50.82	5.96	6.03	3.94
15	205PC	235	0.000	0.00	0.00	0.00	0.00	2.88	4.03	11.55	28.51	23.84	18.62	10.57	0.00	46.97	53.03	5.62	6.34	3.76
16	205PC	255	0.000	0.00	0.00	0.00	0.00	0.00	6.52	9.16	25.25	25.36	21.52	12.18	0.00	40.93	59.06	5.12	6.00	3.37
17	205PC	275	0.000	0.00	0.00	0.00	0.00	0.00	1.14	6.22	26.71	27.75	24.28	13.89	0.00	34.07	65.92	3.57	3.01	2.88
18	205PC	295	0.000	0.00	0.00	0.00	0.00	0.00	5.04	13.88	25.59	26.21	19.80	9.48	0.00	44.51	55.49	5.09	4.62	3.65
19	205PC	315	0.000	0.00	0.00	0.00	0.00	0.00	7.72	7.07	25.02	24.46	22.05	13.69	0.00	39.81	60.20	5.16	6.26	3.24
20	205PC	335	0.000	0.00	0.00	0.00	0.00	0.00	2.61	5.95	22.26	25.29	27.01	16.88	0.00	30.82	69.18	3.55	3.51	2.45
21	205PC	355	0.000	0.00	0.00	0.00	0.00	0.00	3.16	4.63	26.69	28.07	24.65	12.81	0.00	34.48	65.53	4.24	5.35	2.97
22	205PC	375	0.000	0.00	0.00	0.00	0.00	0.00	2.79	6.83	26.55	27.85	22.95	13.02	0.00	36.17	63.82	3.93	3.53	3.00
23	205PC	395	0.000	0.00	0.00	0.00	0.00	0.00	4.04	6.09	25.47	27.80	23.93	12.66	0.00	35.60	64.39	4.12	4.32	2.93
24	205PC	415	0.000	0.00	0.00	0.00	0.00	4.37	2.11	4.89	25.77	26.78	23.95	12.13	0.00	37.14	62.85	5.03	7.24	2.98
25	205PC	435	0.000	0.00	0.00	0.00	0.00	3.90	7.72	11.15	23.72	22.98	20.00	10.55	0.00	46.49	53.53	6.81	0.47	3.71
26	205PC	455	0.000	0.00	0.00	0.00	5.13	0.00	4.57	10.41	26.35	24.91	18.73	9.89	0.00	46.46	53.53	6.86	9.76	3.77
27	205PC	475	0.000	0.00	0.00	0.00	0.00	0.00	4.73	6.77	31.52	30.82	18.17	7.99	0.00	43.02	56.98	4.75	4.72	3.59
28	205PC	495	0.000	0.00	0.00	0.00	0.00	3.34	0.89	6.37	30.41	30.31	19.40	9.28	0.00	41.01	58.99	4.92	6.32	3.48
29	205PC	515	0.000	0.00	0.00	0.00	0.00	2.25	2.62	6.33	33.45	29.57	17.83	7.95	0.00	44.65	55.35	4.84	5.22	3.66
30	205PC	535	0.000	0.00	0.00	0.00	0.00	4.43	1.17	8.34	31.97	30.20	17.04	6.84	0.00	45.91	54.08	5.55	6.77	3.78
31	206PC	80	0.000	0.00	0.00	0.00	0.00	4.44	1.41	9.86	20.23	20.55	26.21	17.31	0.00	35.94	64.07	5.02	6.01	2.63
32	206PC	100	0.000	0.00	0.00	0.00	0.00	0.00	0.00	3.17	14.01	24.26	33.17	25.38	0.00	17.18	82.81	2.45	2.21	1.59
33	206PC	120	0.000	0.00	0.00	0.00	0.00	0.84	11.16	5.33	14.13	16.77	28.67	23.10	0.00	31.46	68.54	5.43	7.94	1.89
34	206PC	140	0.000	0.00	0.00	0.00	0.00	0.00	2.84	4.44	26.92	27.56	24.80	13.44	0.00	34.20	65.80	3.86	3.00	2.88
35	206PC	160	0.000	0.00	0.00	0.00	0.00	0.00	1.41	5.20	23.98	28.15	29.17	12.09	0.00	30.59	69.41	3.44	3.14	2.61
36	206PC	180	0.000	0.00	0.00	0.00	0.00	0.00	0.78	10.37	29.48	29.38	21.71	8.30	0.00	40.63	59.37	4.17	3.35	3.38
37	206PC	200	0.000	0.00	0.00	0.00	0.00	0.00	1.46	6.79	25.71	29.13	26.49	10.43	0.00	33.96	66.05	3.67	3.80	2.88
38	206PC	220	0.000	0.00	0.00	0.00	0.00	3.24	1.68	4.20	27.00	27.82	25.31	10.75	0.00	36.12	63.88	4.49	5.94	2.94
39	206PC	240	0.000	0.00	0.00	0.00	0.00	0.00	2.54	4.19	24.91	31.08	26.90	10.37	0.00	31.64	68.35	3.73	3.71	2.81
40	206PC	260	0.000	0.00	0.00	0.00	0.00	0.00	4.66	8.19	28.73	28.81	21.48	8.13	0.00	41.58	58.42	4.78	5.07	3.46
41	206PC	280	0.000	0.00	0.00	0.00	0.00	2.70	5.87	8.31	27.27	26.72	20.86	8.28	0.00	44.15	55.86	5.76	6.94	3.61
42	206PC	300	0.000	0.00	0.00	0.00	0.00	2.49	8.36	10.55	28.33	24.32	18.67	7.28	0.00	49.73	50.27	6.78	0.02	3.98
43	206PC	320	0.000	0.00	4.95	8.91	9.15	10.82	20.63	19.74	17.03	6.42	1.85	0.50	13.86	77.37	8.77	28.48	26.53	18.89
44	206PC	340	0.000	0.00	0.00	0.00	0.00	0.00	0.00	10.06	29.24	29.82	22.50	8.39	0.00	39.30	60.71	4.00	3.10	3.31
45	206PC	360	0.000	0.00	0.00	15.71	5.50	6.71	16.08	13.97	18.71	13.05	7.51	2.75	15.71	60.97	23.31	23.37	25.12	11.59
46	206PC	380	0.000	0.00	0.00	0.00	0.00	8.03	5.92	11.98	27.59	23.03	17.05	6.39	0.00	53.52	46.47	8.45	10.50	4.28
47	206PC	400	0.000	0.00	0.00	3.27	8.58	7.83	8.89	12.67	25.67	17.98	10.47	4.63	3.27	63.64	33.08	15.24	10.22	5.92
48	206PC	420	0.000	0.00	0.00	0.00	4.56	4.36	9.14	10.43	23.35	22.72	18.37	7.06	0.00	51.84	48.15	9.26	12.42	4.14
49	206PC	440	0.000	0.00	0.00	3.26	11.55	3.03	7.72	14.55	26.68	19.59	10.25	3.37	3.26	63.53	33.21	15.52	20.49	6.81
50	206PC	460	0.000	0.00	0.00	0.00	0.00	0.00	4.91	8.66	31.10	29.95	18.70	6.69	0.00	44.67	55.34	5.04	5.13	3.70

TABLE 2: Bulk Mineralogy of Lake Winnipeg sediments

SAMPLE			MINERALOGY																	XRD		
			Silicates						Carbonates							Evaporites			Sulphides			
Seq. No	Site ID	Depth (cm)	Quartz %	K-spar %	Plag %	TotFeld %	Amphib %	TotClays %	Calcite %	Mg-Calc %	Protodol %	Dolomite %	Monohydcal %	Aragonite %	Magnesite %	Na-sulfate %	Anhydrite %	Gypsum %	Pyrite %	Mg in Cal %	Mg in HMC %	Ca in PDol %
1	204PC	530	9.39	0.00	11.58	11.58	2.49	58.16	0.00	7.43	0.00	12.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00		7.43	
2	204PC	550	9.23	0.00	10.79	10.79	0.00	58.34	0.00	8.03	0.00	11.80	3.80	0.00	0.00	0.00	0.00	0.00	0.00		9.02	
3	204PC	570	5.35	5.18	8.41	13.59	1.55	42.83	0.00	6.71	2.72	8.32	0.00	0.00	0.00	2.32	16.62	0.00	0.00		8.68	78.01
4	205PC	15	10.15	0.00	0.00	0.00	0.00	70.85	0.00	0.00	3.79	7.28	0.00	0.00	0.00	0.00	0.00	7.93	0.00			75.18
5	205PC	35	12.97	0.00	0.00	0.00	0.00	68.71	0.00	0.00	0.00	14.11	0.00	0.00	0.00	4.21	0.00	0.00	0.00			
6	205PC	55	6.17	0.00	5.40	5.40	2.32	47.60	0.00	0.00	3.67	7.33	0.00	0.00	2.03	0.00	18.36	0.00	7.11			55.27
7	205PC	75	26.46	15.00	18.70	33.70	2.00	17.56	0.00	8.02	5.62	8.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00		5.77	65.00
8	205PC	95	13.69	0.00	9.16	9.18	2.16	44.75	0.00	14.59	0.00	15.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00		8.68	
9	205PC	115	1.92	0.00	14.15	14.15	0.00	32.27	0.00	14.68	0.00	20.54	0.00	0.00	0.00	0.00	16.44	0.00	0.00		8.62	
10	205PC	135	11.86	5.14	6.29	11.44	2.30	28.69	0.00	11.16	4.37	13.70	0.00	0.00	0.00	0.00	18.47	0.00	0.00		10.24	58.75
11	205PC	155	11.34	0.00	12.31	12.31	2.68	45.86	0.00	12.56	0.00	15.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00		8.98	
12	205PC	175	10.74	0.00	9.33	9.33	3.12	28.28	0.00	15.36	0.00	15.67	0.00	0.00	0.00	0.00	17.49	0.00	0.00		8.88	
13	205PC	195	11.90	0.00	11.35	11.35	0.00	23.35	0.00	13.23	3.98	17.04	0.00	0.00	0.00	0.00	19.17	0.00	0.00		7.76	59.67
14	205PC	215	8.46	0.00	8.81	8.81	0.00	53.17	0.00	11.95	3.66	11.37	0.00	0.00	2.58	0.00	0.00	0.00	0.00		7.76	59.49
15	205PC	235	6.70	0.00	7.18	7.18	2.28	48.52	0.00	8.40	3.61	7.72	0.00	0.00	2.70	0.00	12.92	0.00	0.00		6.60	61.38
16	205PC	255	7.00	0.00	9.11	9.11	0.00	50.90	0.00	7.37	3.22	8.49	0.00	0.00	0.00	0.00	13.90	0.00	0.00		7.33	63.00
17	205PC	275	6.56	0.00	9.48	9.48	0.00	53.16	0.00	4.37	3.09	7.36	0.00	0.00	0.00	0.00	15.97	0.00	0.00		6.63	79.20
18	205PC	295	7.85	0.00	8.98	8.98	0.00	52.60	0.00	2.37	3.76	5.97	0.00	0.00	0.00	0.00	18.25	0.00	0.00		9.38	59.09
19	205PC	315	9.80	0.00	12.65	12.65	0.00	67.58	0.00	2.25	0.00	7.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00		6.60	
20	205PC	335	6.86	0.00	12.65	12.65	2.34	56.69	0.00	5.75	3.77	8.84	0.00	0.00	0.00	3.10	0.00	0.00	0.00		7.99	78.55
21	205PC	355	8.01	0.00	9.26	9.26	0.00	58.94	0.00	9.02	4.20	10.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00		6.33	66.63
22	205PC	375	8.84	0.00	13.35	13.35	0.00	31.00	0.00	7.34	4.86	11.34	0.00	0.00	0.00	0.00	23.28	0.00	0.00		7.66	79.81
23	205PC	395	10.61	0.00	17.18	17.18	0.00	42.22	0.00	10.59	7.28	12.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00		5.83	61.66
24	205PC	415	7.48	0.00	13.72	13.72	0.00	71.58	0.00	6.57	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		7.69	59.89
25	205PC	435	7.01	0.00	13.42	13.42	0.00	32.04	0.00	9.60	5.30	9.24	0.00	0.00	0.00	0.00	23.40	0.00	0.00		5.83	61.26
26	205PC	455	7.69	0.00	11.34	11.34	0.00	58.66	0.00	11.82	0.00	10.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00		6.93	
27	205PC	475	9.72	0.00	19.82	19.82	0.00	37.48	0.00	19.13	0.00	13.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00		8.22	
28	205PC	495	9.16	8.41	13.06	21.46	0.00	33.58	0.00	21.54	0.00	14.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00		5.30	
29	205PC	515	10.82	0.00	11.32	11.32	0.00	34.31	0.00	23.69	4.10	15.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00		6.36	59.30
30	205PC	535	9.52	0.00	9.75	9.75	0.00	28.65	0.00	14.70	4.80	13.60	0.00	0.00	0.00	0.00	18.99	0.00	0.00		7.23	60.02
31	206PC	80	4.74	0.00	8.05	8.05	0.00	54.21	0.00	7.33	0.00	6.10	0.00	0.00	0.00	0.00	19.57	0.00	0.00		11.75	
32	206PC	100	4.86	0.00	8.73	8.73	2.31	59.33	0.00	7.69	0.00	5.28	0.00	2.85	0.00	0.00	0.00	8.95	0.00		5.50	
33	206PC	120	6.57	0.00	17.44	17.44	0.00	48.43	0.00	11.11	9.63	8.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00		5.53	72.41
34	206PC	140	5.51	0.00	6.13	6.13	2.01	55.74	0.00	5.80	3.19	5.71	0.00	0.00	0.00	0.00	15.91	0.00	0.00		9.51	57.30
35	206PC	160	8.92	0.00	11.10	11.10	0.00	63.96	0.00	5.91	3.88	6.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00		7.89	58.62
36	206PC	180	8.37	0.00	10.39	10.39	2.54	66.42	0.00	7.61	4.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		8.68	74.45
37	206PC	200	5.53	0.00	9.53	9.53	2.67	63.20	0.00	8.70	4.62	5.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00		9.02	58.22
38	206PC	220	11.05	0.00	18.48	18.48	0.00	46.29	0.00	11.31	0.00	12.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00		7.06	
39	206PC	240	12.17	0.00	0.00	0.00	0.00	52.58	0.00	15.31	8.13	11.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00		10.07	63.78
40	206PC	260	8.54	8.86	15.68	24.54	3.66	35.77	0.00	5.91	5.86	9.13	0.00	6.58	0.00	0.00	0.00	0.00	0.00		11.16	56.10
41	206PC	280	6.24	0.00	8.87	8.87	0.00	51.71	0.00	5.08	3.48	6.59	0.00	0.00	0.00	0.00	18.03	0.00	0.00		9.28	59.43
42	206PC	300	5.78	0.00	9.62	9.62	1.67	53.12	0.00	4.71	3.17	5.54	0.00	0.00	0.00	0.00	16.39	0.00	0.00		9.40	58.78
43	206PC	320	13.41	0.00	17.13	17.13	0.00	41.28	0.00	10.15	6.33	11.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00		8.06	63.81
44	206PC	340	8.65	0.00	11.70	11.70	3.02	29.49	0.00	11.11	4.56	9.50	0.00	0.00	0.00	0.00	21.97	0.00	0.00		7.76	62.90
45	206PC	360	9.21	0.00	10.76	10.76	1.96	54.99	0.00	9.88	3.73	9.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00		7.92	59.86
46	206PC	380	10.20	0.00	0.00	0.00	3.69	48.32	0.00	7.53	3.81	9.15	0.00	0.00	0.00	0.00	17.31	0.00	0.00		8.02	60.36
47	206PC	400	21.58	0.00	18.54	18.54	2.39	22.62	0.00	10.15	4.38	7.69	0.00	0.00	0.00	0.00	12.66	0.00	0.00		6.63	59.21
48	206PC	420	7.55	10.58	24.21	34.80	3.33	19.38	0.00	9.84	3.68	7.43	0.00	0.00	0.00	0.00	13.98	0.00	0.00	3.73		62.34
49	206PC	440	8.31	11.42	10.10	21.51	2.45	35.29	6.10	0.00	3.41	6.73	0.00	0.00	0.00	0.00	18.19	0.00	0.00	2.63		64.15
50	206PC	460	9.18	9.23	13.21	22.45	2.53	43.38	13.38	0.00	0.00	9.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.63		

TABLE 3: Geochemistry of Lake Winnipeg Sediments

SAMPLE			GEOCHEMISTRY																								
Seq. No	Site ID	Depth (cm)	Ag ppm	Al %	Ba ppm	Be ppm	Bi ppm	Ca %	Cd ppm	Co ppm	Cr ppm	Cu ppm	Fe %	K %	Mg %	Mn ppm	Mo ppm	Na %	Ni ppm	P ppm	Pb ppm	Sr ppm	Ti %	V ppm	W ppm	Zn ppm	As ppm
1	204PC	530	<0.2	7.61	610	2.0	<2	5.45	<0.5	17	100	38	3.82	2.50	2.61	620	<1	1.37	45	590	14	194	0.34	105	<10	96	1
2	204PC	550	<0.2	7.61	610	2.0	12	5.54	<0.5	18	100	36	3.81	2.52	2.61	610	<1	1.41	46	610	14	198	0.34	109	<10	96	1
3	204PC	570	<0.2	7.70	620	2.0	2	5.61	<0.5	18	99	36	3.87	2.52	2.65	630	<1	1.44	47	630	12	203	0.34	107	<10	96	4
4	205PC	15	<0.2	7.89	650	2.0	2	2.38	<0.5	17	101	37	4.03	2.32	2.19	755	<1	1.32	47	610	18	191	0.36	124	<10	102	6
5	205PC	35	<0.2	7.96	650	2.0	2	2.61	<0.5	18	107	39	4.07	2.36	2.32	705	<1	1.33	52	620	18	192	0.37	128	<10	104	1
6	205PC	55	<0.2	5.71	520	2.0	8	4.18	<0.5	10	66	18	2.18	1.84	1.81	400	<1	1.52	26	470	10	219	0.23	67	<10	50	6
7	205PC	75	<0.2	8.01	650	1.5	2	2.69	<0.5	19	110	38	4.21	2.44	2.40	675	<1	1.30	51	610	18	194	0.38	127	<10	108	4
8	205PC	95	<0.2	6.34	550	1.5	<2	6.96	<0.5	15	90	29	3.08	2.23	2.57	625	<1	1.30	35	500	10	201	0.30	87	<10	76	6
9	205PC	115	<0.2	6.12	530	1.5	8	6.86	<0.5	13	74	27	2.83	2.12	2.67	560	<1	1.33	31	500	14	201	0.28	79	<10	70	2
10	205PC	135	<0.2	6.71	570	2.0	2	6.54	<0.5	16	81	31	3.25	2.30	2.69	580	<1	1.40	39	520	12	203	0.30	89	<10	80	2
11	205PC	155	<0.2	6.77	600	2.0	10	6.75	<0.5	18	94	35	3.59	2.43	2.74	610	<1	1.36	46	570	12	208	0.34	101	<10	90	1
12	205PC	175	<0.2	6.98	590	2.0	8	6.89	<0.5	17	99	34	3.60	2.41	2.68	595	<1	1.34	43	560	12	205	0.33	99	<10	88	1
13	205PC	195	<0.2	7.30	600	2.0	2	6.80	<0.5	18	97	34	3.65	2.48	2.70	585	<1	1.35	40	580	16	205	0.32	100	<10	90	1
14	205PC	215	0.4	7.50	610	2.0	6	6.25	<0.5	18	100	36	3.81	2.51	2.60	595	<1	1.35	43	570	14	202	0.33	103	<10	94	1
15	205PC	235	0.4	7.70	620	2.0	2	4.93	<0.5	18	103	37	3.93	2.56	2.43	595	<1	1.35	47	570	16	194	0.33	104	<10	98	2
16	205PC	255	0.2	7.83	680	2.5	6	4.70	<0.5	21	106	42	4.36	2.70	2.50	660	<1	1.43	52	650	16	211	0.37	117	<10	108	2
17	205PC	275	<0.2	8.31	710	2.5	6	3.14	<0.5	21	109	43	4.51	2.76	2.40	675	<1	1.50	54	640	16	209	0.38	124	<10	114	1
18	205PC	295	<0.2	8.56	730	2.5	2	2.09	<0.5	22	108	43	4.65	2.95	2.24	615	<1	1.53	52	710	20	202	0.41	118	<10	114	1
19	205PC	315	<0.2	8.59	770	3.0	6	1.83	<0.5	23	111	46	5.01	3.12	2.31	675	<1	1.56	55	680	20	203	0.43	123	<10	124	2
20	205PC	335	<0.2	8.68	710	2.5	4	3.14	<0.5	22	112	43	4.82	2.96	2.50	695	<1	1.37	53	650	18	195	0.39	119	<10	116	1
21	205PC	355	<0.2	8.27	680	2.5	8	4.09	<0.5	21	113	42	4.54	2.84	2.53	710	<1	1.40	52	600	20	196	0.38	114	<10	110	1
22	205PC	375	<0.2	8.36	680	2.5	6	3.91	<0.5	20	108	41	4.37	2.81	2.58	690	<1	1.47	52	610	18	199	0.38	112	<10	108	1
23	205PC	395	<0.2	8.25	680	2.5	6	4.53	<0.5	21	111	43	4.46	2.76	2.58	720	<1	1.40	55	590	14	197	0.37	112	<10	108	4
24	205PC	415	<0.2	8.60	700	2.5	8	4.17	<0.5	22	116	44	4.66	2.88	2.67	700	<1	1.44	53	620	20	202	0.38	117	<10	114	1
25	205PC	435	<0.2	7.55	640	2.0	2	4.69	0.5	21	111	40	4.34	2.67	2.55	650	<1	1.37	52	560	18	191	0.35	109	<10	106	1
26	205PC	455	<0.2	6.95	600	2.0	8	7.10	<0.5	17	99	35	3.61	2.45	2.73	595	<1	1.33	42	550	12	204	0.32	96	<10	88	2
27	205PC	475	<0.2	6.82	600	2.0	6	7.83	0.5	17	105	37	3.80	2.46	2.56	600	<1	1.32	47	590	12	209	0.33	105	<10	94	1
28	205PC	495	<0.2	6.01	530	1.5	10	9.43	<0.5	17	96	33	3.35	2.12	2.43	610	<1	1.14	41	520	10	200	0.31	92	<10	82	1
29	205PC	515	<0.2	6.22	560	2.0	4	7.86	0.5	17	94	34	3.47	1.80	2.42	570	<1	1.23	42	540	12	202	0.32	96	<10	86	1
30	205PC	535	<0.2	6.76	600	2.0	10	7.87	<0.5	17	100	35	3.61	2.41	2.62	595	<1	1.34	42	570	12	215	0.34	102	<10	88	1
31	206PC	80	0.6	7.36	630	2.0	6	4.57	<0.5	20	111	39	4.38	2.47	2.10	755	<1	1.22	52	590	14	186	0.33	115	<10	106	1
32	206PC	100	<0.2	7.99	630	2.0	2	5.09	0.5	20	118	38	4.32	2.61	2.23	695	<1	1.32	53	580	14	193	0.34	117	<10	106	4
33	206PC	120	<0.2	8.67	640	2.5	<2	3.40	<0.5	22	128	44	5.02	2.69	2.22	650	<1	1.27	62	650	18	183	0.37	129	10	118	2
34	206PC	140	<0.2	7.72	600	1.0	10	3.69	0.5	18	115	41	4.54	2.50	2.20	660	<1	1.05	49	590	18	168	0.35	109	10	110	1
35	206PC	160	0.6	7.66	590	2.0	8	3.90	<0.5	18	114	40	4.23	2.43	2.24	645	<1	1.07	50	580	18	169	0.34	104	<10	104	1
36	206PC	180	0.8	8.02	640	2.0	<2	3.71	<0.5	19	119	43	4.38	2.56	2.33	730	<1	1.41	53	570	16	203	0.36	120	<10	108	1
37	206PC	200	<0.2	7.80	620	2.0	6	4.68	<0.5	20	116	42	4.34	2.51	2.35	760	<1	1.36	52	560	14	203	0.36	114	<10	106	1
38	206PC	220	<0.2	7.85	630	2.0	4	4.03	<0.5	20	111	42	4.38	2.47	2.26	710	<1	1.31	54	560	14	195	0.35	119	<10	108	1
39	206PC	240	<0.2	8.10	650	2.0	8	4.14	<0.5	21	118	42	4.47	2.57	2.35	765	<1	1.42	52	560	12	203	0.36	118	<10	110	2
40	206PC	260	<0.2	8.44	670	2.0	4	3.69	<0.5	20	121	43	4.54	2.62	2.38	730	<1	1.49	54	560	16	208	0.37	121	<10	112	1
41	206PC	280	<0.2	8.20	650	2.0	4	3.70	0.5	20	117	42	4.36	2.52	2.28	715	<1	1.42	54	550	14	201	0.35	119	<10	110	1
42	206PC	300	<0.2	8.20	670	2.0	8	3.64	<0.5	20	121	43	4.38	2.55	2.34	735	<1	1.55	54	570	16	213	0.36	118	<10	108	1
43	206PC	320	<0.2	7.88	650	2.0	4	3.43	0.5	19	112	41	4.23	2.45	2.25	675	<1	1.52	54	560	14	210	0.35	113	<10	106	1
44	206PC	340	<0.2	7.78	630	2.0	8	4.95	<0.5	18	112	39	4.05	2.43	2.27	700	<1	1.47	49	550	14	213	0.34	110	<10	100	2
45	206PC	360	<0.2	7.68	650	2.0	10	4.69	<0.5	18	104	38	3.81	2.43	2.24	635	<1	1.70	48	570	14	238	0.34	105	<10	94	1
46	206PC	380	<0.2	7.37	640	1.5	2	4.28	0.5	15	95	33	3.40	2.30	2.06	555	<1	1.78	42	570	16	253	0.31	95	<10	84	1
47	206PC	400	0.4	7.08	600	1.5	<2	6.19	<0.5	16	107	32	3.33	2.26	2.19	565	<1	1.59	43	530	12	234	0.31	93	<10	80	1
48	206PC	420	<0.2	6.98	610	1.5	6	7.57	<0.5	16	100	33	3.35	2.30	2.36	615	<1	1.65	40	530	12	244	0.32	91	<10	80	1
49	206PC	440	<0.2	6.97	620	1.5	<2	6.09	<0.5	14	89	30	3.19	2.24	2.24	550	<1	1.71	38	510	8	246	0.30	88	<10	78	1
50	206PC	460	<0.2	7.00	590	1.5	8	6.68	<0.5	17	100	34	3.40	2.26	2.31	595	<1	1.55	42	490	10	226	0.31	92	<10	82	2

TABLE 4: Carbon content of Lake Winnipeg sediments

SAMPLE			CARBON CONTENT			
Seq. No	Site ID	Depth (cm)	TotalC %	Organic C %	Inorganic %	$CaCO_3$ %
1	204PC	530	2.4	0.3	2.1	17.25
2	204PC	550	2.4	0.3	2.1	17.68
3	204PC	570	2.3	0.3	2.0	16.57
4	205PC	15	1.6	0.5	1.1	9.09
5	205PC	35	1.9	0.6	1.3	10.65
6	205PC	55	1.5	0.4	1.1	9.01
7	205PC	75	1.7	0.2	1.6	12.92
8	205PC	95	3.2	0.2	3.0	25.24
9	205PC	115	3.1	0.2	2.9	24.44
10	205PC	135	2.8	0.2	2.7	22.26
11	205PC	155	3.0	0.3	2.7	22.51
12	205PC	175	2.9	0.3	2.6	21.98
13	205PC	195	2.9	0.2	2.7	22.38
14	205PC	215	2.7	0.2	2.5	21.18
15	205PC	235	2.1	0.3	1.8	15.28
16	205PC	255	1.9	0.2	1.7	14.12
17	205PC	275	1.3	0.3	1.0	8.52
18	205PC	295	1.0	0.3	0.7	6.23
19	205PC	315	0.9	0.2	0.7	5.54
20	205PC	335	1.6	0.3	1.2	10.36
21	205PC	355	2.0	0.4	1.6	13.68
22	205PC	375	1.7	0.3	1.4	11.49
23	205PC	395	1.9	0.3	1.6	13.28
24	205PC	415	1.7	0.3	1.3	11.16
25	205PC	435	2.1	0.3	1.8	15.19
26	205PC	455	2.9	0.3	2.6	21.68
27	205PC	475	3.3	0.3	2.9	24.55
28	205PC	495	3.8	0.3	3.5	29.12
29	205PC	515	3.7	0.3	3.4	28.48
30	205PC	535	2.8	0.3	2.6	21.30
31	206PC	80	1.9	0.4	1.5	12.78
32	206PC	100	2.2	0.3	1.8	15.38
33	206PC	120	1.6	0.4	1.2	10.03
34	206PC	140	1.8	0.3	1.4	11.73
35	206PC	160	1.7	0.4	1.3	10.93
36	206PC	180	1.7	0.3	1.4	11.44
37	206PC	200	2.1	0.4	1.7	14.49
38	206PC	220	1.6	0.4	1.3	10.48
39	206PC	240	1.9	0.4	1.5	12.45
40	206PC	260	1.5	0.3	1.2	10.03
41	206PC	280	1.6	0.4	1.2	10.08
42	206PC	300	1.7	0.4	1.3	10.96
43	206PC	320	1.6	0.3	1.3	10.45
44	206PC	340	2.1	0.3	1.8	14.95
45	206PC	360	1.9	0.3	1.6	13.28
46	206PC	380	1.9	0.2	1.6	13.63
47	206PC	400	2.5	0.3	2.2	18.51
48	206PC	420	2.8	0.3	2.5	21.01
49	206PC	440	2.3	0.2	2.1	17.20
50	206PC	460	2.9	0.3	2.7	22.23

Appendix 10.9

Stable isotope composition of ostracode valves from Lake Winnipeg North Basin

C.G. Rodrigues[1] and C.F.M. Lewis[2]

1. Earth Sciences, School of Physical Sciences, University of Windsor
2. Geological Survey of Canada (Atlantic)

Samples from CCGS *Namao* cores 96900-205PC and 96900-206PC, ranging in volume from 5 to 12 ml, were wet-sieved in a 63 μm sieve and the residues examined for ostracodes (Rodrigues, 1996). From 2 to 6 valves of *Candona subtriangulata* per sample were analysed for stable isotopic composition ($\delta^{13}C_{PDB}$ and $\delta^{18}O_{PDB}$) at the Stable Isotope Laboratory, Department of Geological Sciences, University of Michigan, Ann Arbor, under the direction of K.C. Lohman and L. Wingate. The analytical method is described in Frank and Lohman (1995). Calibration of measured isotopic enrichments to the V-PDB scale is based on daily analysis of the NBS-19 powdered carbonate standard ($\delta^{13}C$ = 1.95 ‰; $\delta^{18}O$ = -2.2 ‰). The standard deviations for $\delta^{13}C$ and $\delta^{18}O$ (n=59) are 0.07 and 0.04, respectively. The 95% confidence limits for the analysis of this standard are 1.95+/-0.01 for $\delta^{13}C$ and -2.2+/-0.02 for $\delta^{18}O$ (L. Wingate, personal communication, 1998).

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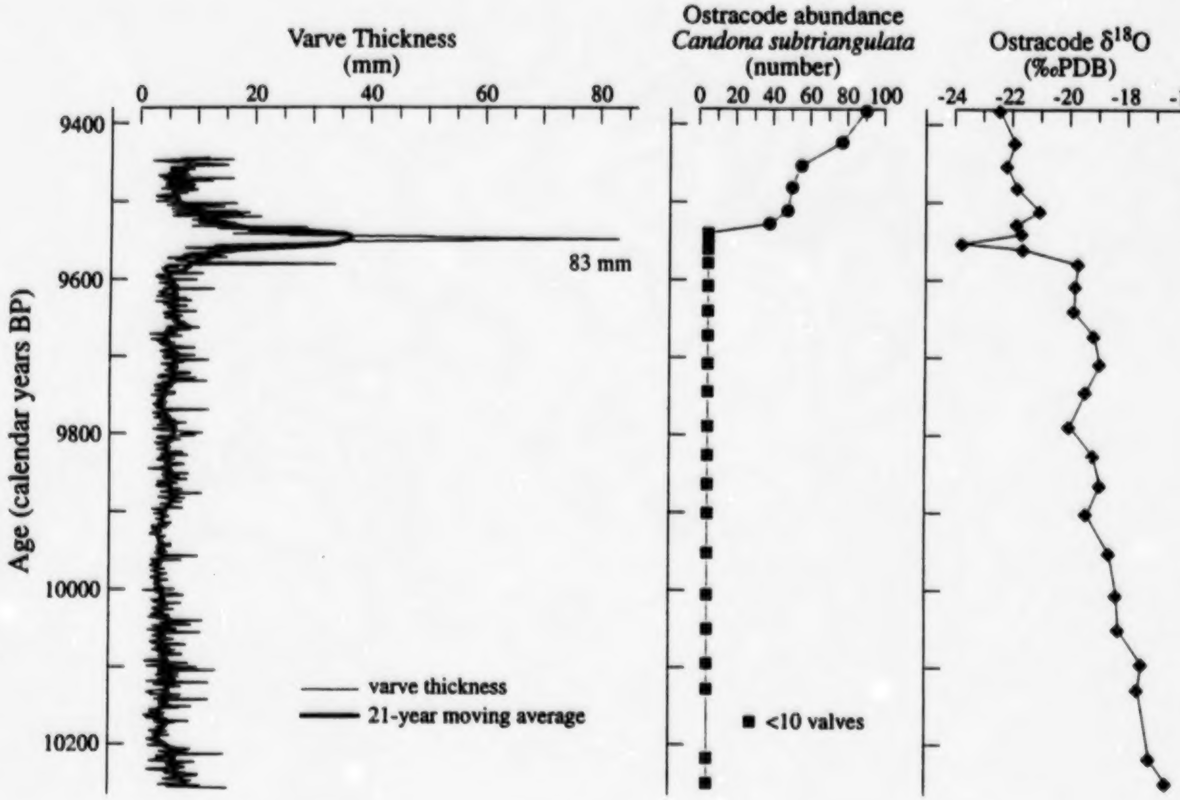

Figure1. Composite record of rhythmite thickness, ostracode abundance and $\delta^{18}O$ isotope composition against calendar age in cores 205PC and 206PC. The top of this record is anchored on paleomagnetic inclination feature I 14. At first, North Basin was deeply inundated by a mixture of meltwater and precipitation runoff as shown by the early, modest values of ostracode $\delta^{18}O$. Meltwater contribution progressively increased upcore (increasingly depleted $\delta^{18}O$), culminating in a massive discharge of meltwater ($\delta^{18}O = -23.7$) and sediment (thick rhythmites) about 9550 cal BP (~8.6 ka) which may have also constructed the Hargrave Moraine. Subsequently, meltwater continued to dominate (light $\delta^{18}O$), but sediment production declined (thinner rhythmites) and ostracodes became more abundant.

Appendix 10.10

Rhythmite thickness in Agassiz Sequence deposits

J. Davison[1], P.J. Henderson[2], C.F.M Lewis[1], E. Nielsen[3], L.H. Thorleifson[2]

1. Geological Survey of Canada (Atlantic)
2. Geological Survey of Canada, Ottawa
3. Manitoba Energy and Mines

The following tables list measured thicknesses of 1884 silty clay rhythmite units found in four cores from the North Basin of Lake Winnipeg. Two cores were collected in 1994 (*Namao* 94-900-105 and -106) and two in 1996 (*Namao* 96-900-205 and -206). For general descriptions of these cores see Lewis and Todd (1996) and Lewis et al. (this volume).

The rhythmites were distinguished primarily on the basis of colour. Each rhythmite typically rests on a sharp base. Most commonly a lower lighter gray layer (5Y4/1) grades up to a darker layer of olive gray (5Y4/2). In places light gray silt laminae (5Y6/1) are present in the lower layer. The rhythmites are interpreted as annual deposits (varves) as suggested by pollen evidence (Anderson and Vance, this volume). The thickest varves in these cores occur in the middle of core 106, from about 300 to 525 cm downcore (Fig. 1).

Individual rhythmites were identified and measured on enlarged prints of the core photographs. The rhythmite measurements of thickness in the photos were then scaled by the ratio of the core interval represented in each photo to the equivalent interval on the photo to obtain the actual rhythmite thicknesses in the core. The measurements were made by Davison under the supervision of Lewis. The data were subsequently reviewed by Henderson, Nielsen and Thorleifson.

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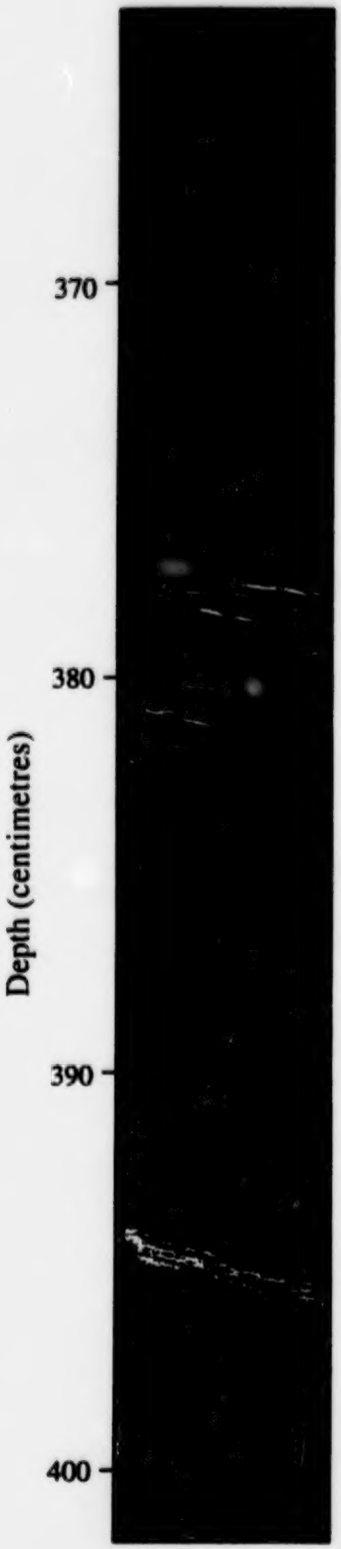

Figure 1. Thick silty clay rhythmites from Lake Agassiz deposits cored in Lake Winnipeg (core 94900-106PC; Lewis et al., this volume). Each rhythmite consists of a light-coloured carbonate-rich basal layer (here a set of laminations) capped with a dark clay-rich layer. The interpretation of the rhythmites as annual deposits or varves is consistent with the chronology of ice retreat in the region.

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106	
Rhythmite number in core	Thickness in core (mm)	Rhythmite number in core	Thickness in core (mm)
1	4.6	1	5.9
2	4.6	2	5.7
3	6.7	3	6.7
4	7.4	4	4.7
5	8.9	5	3.5
6	5.9	6	12.8
7	6.3	7	5.5
8	5.6	8	8.1
9	7.6	9	4.3
10	8.4	10	6.5
11	6.9	11	8.4
12	7.6	12	5.7
13	6.9	13	8.6
14	9.0	14	6.7
15	7.2	15	4.7
16	8.0	16	4.3
17	5.0	17	5.9
18	5.0	18	5.9
19	8.4	19	6.7
20	3.4	20	3.3
21	6.1	21	5.5
22	7.2	22	7.5
23	10.7	23	4.9
24	3.8	24	12.6
25	6.1	25	2.4
26	5.3	26	6.3
27	5.0	27	4.9
28	6.9	28	5.1
29	5.0	29	4.3
30	7.4	30	2.4
31	8.4	31	3.1
32	4.2	32	3.9
33	8.4	33	3.1
34	5.0	34	4.1
35	6.9	35	4.3
36	3.8	36	6.3
37	5.3	37	8.4
38	6.9	38	12.1
39	4.8	39	8.6
40	13.0	40	9.5
41	5.3	41	5.2
42	7.6	42	11.2
43	7.4	43	10.8
44	7.2	44	4.8
45	6.3	45	11.2
46	16.8	46	4.8
47	10.3	47	16.9
48	9.5	48	15.6
49	6.1	49	9.5
50	11.3	50	9.1
51	6.1	51	5.0
52	6.9	52	6.9
53	7.8	53	3.9
54	9.1	54	6.7
55	8.7	55	7.6
56	9.5	56	4.3
57	12.4	57	13.8
58	6.1	58	12.1
59	5.4	59	6.0
60	7.6	60	16.4
61	8.7	61	6.0
62	6.1	62	8.6
63	8.7	63	6.0
64	4.3	64	29.4
65	6.9	65	7.3
66	9.5	66	8.6
67	6.9	67	16.6
68	6.1	68	12.3
69	2.8	69	18.5
70	3.3	70	11.4
71	6.9	71	5.3

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106	
72	5.2	72	24.6
73	11.7	73	8.4
74	4.3	74	6.2
75	3.7	75	8.4
76	13.9	76	13.2
77	4.7	77	14.1
78	3.9	78	16.3
79	11.7	79	6.2
80	5.4	80	11.4
81	5.4	81	7.9
82	9.3	82	9.2
83	5.4	83	16.7
84	12.5	84	15.0
85	4.7	85	15.0
86	5.1	86	12.3
87	11.3	87	10.1
88	5.1	88	16.7
89	13.4	89	13.2
90	9.7	90	17.6
91	9.1	91	19.7
92	7.4	92	22.7
93	8.2	93	18.0
94	6.2	94	14.6
95	7.0	95	19.7
96	11.7	96	33.0
97	16.3	97	25.7
98	17.1	98	26.6
99	5.1	99	33.4
100	4.3	100	21.0
101	32.8	101	21.4
102	19.7	102	14.6
103	23.5	103	39.4
104	20.8	104	22.9
105	23.0	105	33.9
106	18.6	106	43.1
107	21.9	107	60.1
108	18.0	108	46.7
109	21.9	109	30.5
110	11.3	110	62.9
111	8.6	111	64.8
112	8.6	112	34.1
113	10.1	113	36.3
114	8.6	114	34.1
115	11.6	115	37.1
116	7.0	116	44.5
117	9.2	117	48.9
118	11.6	118	36.4
119	14.1	119	11.3
120	6.7	120	36.4
121	11.3	121	21.6
122	12.2	122	30.7
123	6.7	123	41.1
124	4.9	124	30.7
125	4.0	125	42.9
126	5.8	126	39.0
127	14.1	127	46.6
128	7.3	128	51.6
129	15.9	129	49.8
130	6.4	130	38.9
131	3.4	131	16.3
132	5.5	132	61.6
133	8.9	133	65.2
134	12.2	134	65.7
135	7.6	135	40.9
136	9.8	136	44.3
137	12.2	137	82.6
138	15.3	138	36.5
139	5.5	na	30.0
140	8.2	139	16.2
141	8.2	140	68.1
142	7.3	141	53.5
143	3.6	142	26.0
144	4.9	143	24.7
145	4.0	144	26.0
146	4.0	145	43.0

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106	
147	5.7	146	32.9
148	5.7	147	12.2
149	5.5	148	17.4
150	8.7	149	8.5
151	6.1	150	26.5
152	9.9	151	28.6
153	7.5	152	49.8
154	6.5	153	33.9
155	6.3	154	26.5
156	9.5	155	8.5
157	10.3	156	13.8
158	11.5	157	3.2
159	4.9	158	6.4
160	6.5	159	6.4
161	6.3	160	15.4
162	6.3	161	9.5
163	5.5	162	13.2
164	7.1	163	50.7
165	4.7	164	54.0
166	6.7	165	22.1
167	5.5	166	25.3
168	4.5	167	17.2
169	6.3	168	10.6
170	4.9	169	8.6
171	4.0	170	11.0
172	6.1	171	17.2
173	4.5	172	8.6
174	7.5	173	18.0
175	4.2	174	4.3
176	5.5	175	5.9
177	7.9	176	6.9
178	5.3	177	4.5
179	4.9	178	12.7
180	9.5	179	5.3
181	10.5	180	8.2
182	4.9	181	9.0
183	7.1	182	11.2
184	5.5	183	12.8
185	6.3	184	12.4
186	8.3	185	8.0
187	7.3	186	16.7
188	11.1	187	6.4
189	9.9	188	3.6
190	7.6	189	10.8
191	5.9	190	5.8
192	6.3	191	8.4
193	8.4	192	14.0
194	11.4	193	3.2
195	9.3	194	10.8
196	5.9	195	4.8
197	9.0	196	12.8
198	5.0	197	4.8
199	6.9	198	8.8
200	7.4	199	6.0
201	6.1	200	8.4
202	10.7	201	4.0
203	7.2	202	5.6
204	9.7	203	2.8
205	6.7	204	5.4
206	8.0	205	2.4
207	5.9	206	9.2
208	11.1	207	8.8
209	7.4	208	4.0
210	8.0	209	4.6
211	9.7	210	4.0
212	9.3	211	3.6
213	6.9	212	8.0
214	5.3	213	10.8
215	5.9	214	6.8
216	5.0	215	8.8
217	6.5	216	7.6
218	5.7	217	7.6
219	3.4	218	8.0
220	4.8	219	9.2
221	5.5	220	7.8

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106	
222	2.5	221	24.9
223	7.2	222	5.1
224	7.8	223	10.1
225	4.8	224	7.4
226	9.0	225	11.1
227	7.2	226	17.0
228	6.3	227	11.1
229	4.0	228	12.0
230	7.4	229	17.5
231	5.9	230	25.8
232	6.3	231	20.3
233	7.4	232	25.8
234	10.4	233	5.5
235	3.5	234	12.0
236	11.0	235	7.1
237	6.7	236	6.9
238	5.2	237	13.6
239	5.2	238	6.9
240	10.0	239	7.8
241	6.3	240	5.1
242	5.4	241	12.0
243	5.6	242	3.7
244	5.2	243	5.1
245	4.3	244	6.9
246	6.9	245	6.4
247	3.0	246	7.8
248	5.8	247	5.1
249	6.3	248	7.4
250	8.2	249	10.2
251	5.0	250	6.2
252	5.8	251	4.4
253	5.2	252	4.8
254	6.3	253	4.4
255	5.2	254	2.6
256	5.4	255	2.6
257	5.8	256	5.1
258	7.4	257	2.6
259	6.9	258	3.7
260	4.8	259	2.9
261	6.9	260	2.6
262	6.5	261	4.4
263	5.2	262	3.7
264	7.1	263	4.0
265	5.2	264	4.0
266	6.3	265	5.1
267	6.5	266	5.5
268	6.3	267	4.4
269	6.3	268	4.4
270	5.2	269	2.9
271	6.9	270	2.9
272	2.2	271	4.9
273	7.8	272	3.7
274	4.3	273	3.1
275	7.1	274	13.5
276	5.4	275	4.0
277	5.0	276	3.3
278	3.5	277	3.5
279	3.7	278	3.3
280	3.9	279	3.7
281	5.2	280	3.3
282	4.3	281	3.1
283	5.8	282	1.5
284	5.4	283	3.3
285	3.7	284	2.9
286	5.0	285	2.6
287	4.3	286	7.3
288	4.3	287	5.8
289	5.2	288	3.1
290	5.2	289	11.0
291	6.3	290	7.3
292	5.0	291	4.0
293	7.4	292	3.7
294	6.7	293	4.7
295	5.2	294	3.9
296	4.8	295	5.8

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106	
297	4.1	296	4.7
298	3.5	297	5.5
299	5.2	298	5.8
300	9.1	299	3.7
301	6.5	300	3.5
302	6.9	301	6.4
303	6.9	302	5.3
304	3.7	303	8.6
305	5.4	304	5.3
306	8.1	305	5.3
307	4.8	306	15.6
308	7.8	307	9.2
309	10.9	308	5.1
310	8.4	309	4.1
311	5.7	310	5.7
312	7.8	311	4.7
313	6.9	312	6.8
314	16.0	313	6.6
315	5.4	314	5.1
316	8.4	315	5.5
317	6.6	316	3.1
318	6.6	317	3.9
319	6.0	318	5.5
320	12.1	319	7.0
321	5.1	320	3.9
322	8.7	321	5.2
323	8.7	322	3.4
324	6.0	323	5.0
325	9.7	324	5.0
326	10.0	325	4.0
327	4.8	326	5.0
328	8.7	327	5.9
329	7.5	328	4.2
330	7.5	329	3.8
331	7.5	330	3.1
332	15.7	331	4.2
333	5.7	332	2.9
334	4.8	333	2.9
335	6.3	334	8.0
336	5.4	335	6.9
337	4.8	336	12.6
338	7.2	337	7.3
339	12.1	338	10.9
340	6.3	339	9.2
341	7.8	340	4.2
342	5.4	341	6.9
343	7.8	342	5.0
344	7.8	343	6.1
345	6.3	344	5.9
346	4.5	345	5.7
347	4.8	346	5.0
348	6.6	347	5.0
349	6.6	348	14.7
350	5.4	349	4.6
351	4.8	350	6.3
352	6.9	351	4.2
353	6.0	352	7.8
354	13.6	353	8.0
355	2.9	354	5.5
356	2.3	355	4.8
357	5.8	356	4.6
358	1.5	357	4.2
359	3.8	358	11.8
360	4.1	359	6.3
361	2.8	360	6.1
362	3.5	361	3.3
363	3.1	362	11.0
364	3.4	363	5.3
365	2.6	364	6.5
366	2.9	365	4.1
367	2.9	366	6.3
368	2.9	367	3.3
369	3.2	368	6.9
370	2.9	369	9.4
371	6.7	370	7.5

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106	
372	4.5	371	7.1
373	7.3	372	5.5
374	4.4	373	5.7
375	2.3	374	5.7
376	7.3	375	4.5
377	9.1	376	5.7
378	3.9	377	8.6
379	7.6	378	3.3
380	10.1	379	7.3
381	3.9	380	4.5
382	2.9	381	5.3
383	2.3	382	6.5
384	3.2	383	3.7
385	1.9	384	6.3
386	4.2	385	5.5
387	2.6	386	4.1
388	2.6	387	3.5
389	7.0	388	4.1
390	8.2	389	4.1
391	3.5	390	5.5
392	3.7	391	6.7
393	5.1	392	5.7
394	3.2	393	5.3
395	4.5	394	6.1
396	7.0	395	15.1
397	5.3	396	4.5
398	4.7	397	5.7
399	7.0	398	6.5
400	2.3	399	4.5
401	3.5	400	4.9
402	3.8	401	8.4
403	9.6	402	6.5
404	3.7	403	8.4
405	5.8	404	5.7
406	5.0	405	5.5
407	5.6	406	3.9
408	14.9	407	4.1
409	8.3	408	5.0
410	4.5	409	6.0
411	11.6	410	6.3
412	5.8	411	6.8
413	5.0	412	10.8
414	9.3	413	5.8
415	7.4	414	10.6
416	9.9	415	10.1
417	3.9	416	6.0
418	7.4	417	3.5
419	4.1	418	9.3
420	5.0	419	4.8
421	10.3	420	5.0
422	3.3	421	5.8
423	5.6	422	6.0
424	5.8	423	6.5
425	7.2	424	5.6
426	2.9	425	8.8
427	5.8	426	6.5
428	8.3	427	10.8
429	6.6	428	6.0
430	4.5	429	8.1
431	5.4	430	10.6
432	4.1	431	9.1
433	2.7	432	5.5
434	3.3	433	6.0
435	5.8	434	15.6
436	4.1	435	5.5
437	5.0	436	8.1
438	8.9	437	6.0
439	3.3	438	5.0
440	2.7	439	7.1
441	7.4	440	7.3
442	9.9	441	11.1
443	2.5	442	6.5
444	4.1	443	7.1
445	3.7	444	5.5
446	8.7	445	6.0

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106	
447	3.3	446	7.6
448	4.5	447	5.0
449	6.4	448	7.1
450	4.1	449	3.5
451	6.6	450	4.3
452	5.2	451	5.8
453	10.1	452	15.7
454	18.4	453	8.4
455	4.8	454	19.1
456	5.2	455	14.6
457	11.8	456	10.1
458	6.1	457	11.2
459	22.1	458	11.2
460	13.1	459	8.4
461	11.4	460	10.7
462	5.2	461	24.2
463	7.9	462	27.8
464	7.9	463	19.1
465	7.9	464	14.1
466	8.3	465	13.5
467	21.4	466	11.2
468	10.5	467	8.4
469	17.5	468	15.5
470	14.9	469	11.8
471	15.1	470	10.7
472	15.1	471	6.2
473	10.9	472	8.4
474	7.9	473	9.0
475	14.0	474	18.5
476	6.1		
477	7.0		
478	6.6		
479	7.9		
480	7.9		
481	10.1		
482	3.5		
483	11.4		
484	13.6		
485	4.4		
486	7.0		
487	10.5		
488	7.9		
489	7.4		
490	3.5		
491	7.9		
492	6.2		
493	4.9		
494	3.7		
495	5.3		
496	11.1		
497	7.2		
498	6.6		
499	9.8		
500	15.0		
501	8.4		
502	5.3		
503	4.5		
504	5.7		
505	6.6		
506	4.1		
507	12.7		
508	7.0		
509	5.5		
510	9.8		
511	6.4		
512	9.8		
513	10.3		
514	9.0		
515	7.8		
516	5.3		
517	15.2		
518	3.3		
519	4.5		
520	3.7		
521	6.6		

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

94-900-105		94-900-106
522	11.9	
523	11.5	
524	10.3	
525	11.7	
526	4.9	
527	13.9	
528	4.5	
529	8.1	
530	17.5	
531	7.4	
532	4.5	
533	6.3	
534	12.6	
535	6.1	
536	7.4	
537	8.5	
538	4.9	
539	2.9	
540	7.2	
541	5.6	
542	7.2	
543	10.1	
544	7.2	
545	15.3	
546	11.5	
547	4.9	
548	11.7	
549	9.0	
550	8.1	
551	9.2	
552	12.1	
553	4.0	
554	5.4	
555	5.8	
556	3.0	
557	8.1	
558	7.1	
559	10.8	
560	13.4	
561	5.8	
562	12.1	
563	6.5	
564	12.8	
565	10.6	
566	13.6	
567	10.1	
568	7.1	
569	13.6	
570	5.0	
571	6.0	
572	7.1	
573	9.1	
574	15.1	
575	8.3	
576	9.1	
577	5.5	
578	5.7	
579	8.4	
580	11.9	
581	16.1	
582	16.7	
583	11.4	
584	11.0	
585	19.4	
586	10.6	
587	15.0	
588	4.8	
589	6.2	
590	18.0	
591	15.6	
592	12.8	
593	8.4	
594	5.3	
595	7.5	

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205		Core 96-900-206	
Rhythmite number in core	Thickness in core (mm)	Rhythmite number in core	Thickness in core (mm)
1	11.9	1	58.0
2	11.1	2	58.0
3	6.8	3	34.0
4	16.2	4	34.0
5	2.1	5	31.0
6	3.8	6	27.8
7	5.3	7	18.8
8	8.9	8	12.9
9	9.6	9	27.5
10	14.5	10	30.7
11	15.3	11	7.8
12	10.0	12	14.9
13	6.8	13	11.7
14	5.1	14	20.7
15	5.1	15	15.9
16	9.4	16	11.3
17	5.1	17	16.3
18	6.4	18	8.5
19	6.8	19	9.0
20	6.8	20	7.6
21	4.7	21	14.2
22	5.1	22	7.1
23	8.5	23	15.1
24	3.0	24	4.7
25	3.8	25	8.5
26	3.4	26	6.6
27	8.1	27	6.1
28	16.2	28	7.6
29	3.9	29	9.5
30	6.9	30	9.9
31	12.6	31	25.5
32	4.5	32	34.0
33	9.1	33	5.2
34	4.3	34	4.5
35	5.6	35	4.3
36	9.5	36	6.6
37	4.3	37	3.8
38	6.3	38	4.7
39	9.3	39	4.5
40	4.3	40	4.0
41	3.5	41	5.2
42	10.0	42	4.3
43	9.5	43	5.7
44	5.4	44	11.1
45	5.8	45	5.9
46	8.2	46	2.9
47	6.9	47	2.9
48	5.2	48	2.7
49	3.9	49	5.3
50	2.6	50	4.9
51	6.9	51	3.3
52	3.0	52	10.0
53	6.1	53	4.7
54	4.3	54	5.8
55	4.8	55	5.1
56	4.3	56	3.3
57	2.6	57	6.2
58	6.1	58	4.3
59	5.3	59	6.7
60	16.8	60	5.8
61	9.7	61	6.7
62	4.4	62	6.5
63	7.1	63	4.0
64	14.6	64	13.0
65	8.8	65	5.1
66	7.1	66	4.0
67	5.3	67	4.3
68	10.6	68	3.3
69	8.4	69	3.6

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205		Core 96-900-206	
70	16.8	70	5.8
71	5.5	na	20.0
72	19.0	71	5.0
73	10.0	72	4.3
74	6.2	73	2.9
75	17.7	74	4.3
76	5.5	75	4.1
77	21.0	76	8.1
78	15.3	77	5.2
79	10.0	78	7.5
80	11.4	79	9.1
81	8.9	80	2.7
82	11.0	81	5.0
83	12.7	82	6.6
84	10.6	83	4.6
85	10.0	84	4.1
86	16.5	85	6.2
87	12.7	86	8.3
88	13.6	87	6.2
89	8.9	88	4.8
90	16.1	89	6.4
91	29.0	90	5.8
92	13.3	91	6.4
93	17.3	92	6.2
94	26.6	93	9.9
95	20.4	94	5.0
96	18.6	95	4.1
97	35.9	96	4.3
98	28.4	97	5.0
99	16.0	98	6.2
100	30.2	99	7.5
101	25.7	100	5.4
102	39.9	101	4.3
103	51.0	102	5.0
104	50.1	103	7.0
105	61.6	104	6.2
106	83.3	105	6.2
		106	5.7
		107	7.9
		108	6.6
		109	7.9
		110	8.4
		111	7.3
		112	9.0
		113	4.8
		114	10.5
		115	6.2
		116	4.6
		117	9.0
		118	5.1
		119	4.4
		120	5.3
		121	6.6
		122	1.8
		123	3.1
		124	5.3
		125	7.5
		126	5.3
		127	4.4
		128	3.3
		129	2.0
		130	3.1
		131	5.3
		132	3.1
		133	4.2
		134	6.2
		135	3.5
		136	5.1
		137	4.0
		138	6.4
		139	7.9
		140	9.7

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	141	6.4
	142	4.4
	143	6.0
	144	3.6
	145	6.0
	146	6.0
	147	4.2
	148	5.0
	149	8.1
	150	9.7
	151	4.0
	152	4.8
	153	6.2
	154	4.2
	155	8.9
	156	12.1
	157	6.8
	158	5.6
	159	7.7
	160	4.8
	161	3.8
	162	5.0
	163	5.6
	164	4.8
	165	5.8
	166	5.6
	167	5.0
	168	6.4
	169	4.4
	170	5.0
	171	5.6
	172	8.9
	173	8.9
	174	8.5
	175	4.2
	176	3.5
	177	3.7
	178	3.2
	179	10.0
	180	6.3
	181	6.2
	182	6.7
	183	11.8
	184	4.0
	185	5.6
	186	6.3
	187	3.7
	188	2.8
	189	2.5
	190	5.6
	191	3.9
	192	4.2
	193	3.9
	194	2.8
	195	4.2
	196	2.8
	197	6.3
	198	6.3
	199	6.3
	200	6.0
	201	2.1
	202	4.6
	203	4.8
	204	3.7
	205	3.5
	206	3.2
	207	4.0
	208	4.2
	209	3.0
	210	4.9
	211	4.6
	212	2.8

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	213	2.5
	214	4.0
	215	3.7
	216	2.8
	217	3.2
	218	4.4
	219	3.2
	220	12.1
	221	6.8
	222	4.0
	223	3.6
	224	2.4
	225	4.6
	226	3.0
	227	4.2
	228	3.2
	229	5.6
	230	2.6
	231	3.0
	232	4.4
	233	6.0
	234	6.4
	235	6.4
	236	3.2
	237	8.3
	238	5.6
	239	6.8
	240	3.2
	241	5.6
	242	5.8
	243	6.4
	244	5.6
	245	2.4
	246	3.2
	247	4.0
	248	7.0
	249	7.9
	250	11.1
	251	8.3
	252	7.3
	253	9.9
	254	9.2
	255	3.4
	256	3.1
	257	3.1
	258	6.1
	259	7.3
	260	4.2
	261	4.4
	262	5.0
	263	2.7
	264	5.4
	265	3.1
	266	4.6
	267	4.6
	268	5.6
	269	4.2
	270	4.4
	271	3.1
	272	5.2
	273	4.6
	274	4.2
	275	7.7
	276	4.6
	277	3.8
	278	7.3
	279	8.6
	280	4.6
	281	3.6
	282	4.0
	283	3.4
	284	6.3

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	285	3.1
	286	4.2
	287	5.7
	288	4.4
	289	4.6
	290	7.7
	291	8.0
	292	6.1
	293	5.0
	294	3.8
	295	5.1
	296	1.7
	297	3.4
	298	5.1
	299	5.9
	300	4.2
	301	5.3
	302	5.3
	303	8.7
	304	4.0
	305	5.9
	306	7.0
	307	5.9
	308	4.2
	309	6.6
	310	8.5
	311	5.1
	312	5.1
	313	3.2
	314	5.1
	315	6.8
	316	3.4
	317	3.8
	318	3.0
	319	3.4
	320	5.7
	321	5.1
	322	5.9
	323	7.6
	324	6.8
	325	5.9
	326	3.8
	327	4.5
	328	11.0
	329	5.3
	330	6.8
	331	7.0
	332	5.9
	333	3.4
	334	8.1
	335	4.7
	336	5.9
	337	5.7
	338	5.1
	339	7.6
	340	5.7
	341	5.3
	342	3.8
	343	5.9
	344	5.9
	345	5.1
	346	6.4
	347	7.7
	348	2.3
	349	3.3
	350	3.9
	351	4.2
	352	3.5
	353	3.9
	354	2.7
	355	3.9
	356	4.6

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	357	5.0
	358	5.4
	359	4.2
	360	4.6
	361	3.1
	362	4.4
	363	4.4
	364	3.9
	365	4.6
	366	5.8
	367	4.0
	368	3.5
	369	5.4
	370	2.3
	371	3.1
	372	5.0
	373	2.3
	374	2.9
	375	3.1
	376	2.7
	377	4.2
	378	2.3
	379	3.9
	380	1.9
	381	3.1
	382	3.5
	383	4.8
	384	4.6
	385	4.0
	386	3.3
	387	3.9
	388	3.5
	389	3.3
	390	3.9
	391	3.9
	392	3.5
	393	5.8
	394	5.0
	395	3.3
	396	5.8
	397	3.1
	398	3.6
	399	3.8
	400	4.2
	401	3.3
	402	3.6
	403	5.1
	404	2.9
	405	4.2
	406	3.3
	407	3.3
	408	5.8
	409	10.4
	410	3.8
	411	4.7
	412	4.0
	413	2.2
	414	7.5
	415	2.7
	416	2.5
	417	2.5
	418	3.3
	419	2.5
	420	2.0
	421	2.5
	422	2.9
	423	3.6
	424	3.8
	425	4.7
	426	3.6
	427	2.2
	428	3.1

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	429	3.5
	430	3.1
	431	5.1
	432	3.1
	433	4.4
	434	3.1
	435	2.4
	436	2.2
	437	3.6
	438	3.6
	439	5.3
	440	2.9
	441	3.1
	442	3.6
	443	3.6
	444	2.7
	445	3.6
	446	3.6
	447	4.0
	448	3.3
	449	2.9
	450	3.1
	451	6.4
	452	0.8
	453	4.5
	454	4.3
	455	3.1
	456	4.3
	457	7.0
	458	5.7
	459	8.0
	460	5.5
	461	3.7
	462	3.7
	463	4.1
	464	3.3
	465	2.3
	466	4.3
	467	2.7
	468	2.9
	469	7.6
	470	4.7
	471	3.9
	472	3.9
	473	5.3
	474	3.9
	475	2.7
	476	2.5
	477	6.3
	478	4.3
	479	3.1
	480	3.1
	481	3.1
	482	3.3
	483	2.3
	484	5.5
	485	2.5
	486	2.9
	487	1.8
	488	5.5
	489	3.3
	490	6.1
	491	5.1
	492	11.3
	493	4.9
	494	3.9
	495	8.4
	496	8.2
	497	9.3
	498	2.5
	499	5.5
	500	3.4

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	501	3.4
	502	6.8
	503	1.7
	504	3.4
	505	6.8
	506	3.0
	507	11.0
	508	6.1
	509	3.6
	510	3.4
	511	2.5
	512	4.2
	513	4.4
	514	3.4
	515	5.5
	516	6.3
	517	3.6
	518	2.5
	519	2.1
	520	3.4
	521	2.5
	522	7.4
	523	8.5
	524	3.4
	525	3.8
	526	3.0
	527	5.5
	528	5.7
	529	2.5
	530	6.6
	531	3.4
	532	3.8
	533	5.9
	534	4.7
	535	7.8
	536	7.6
	537	3.6
	538	4.0
	539	4.2
	540	4.0
	541	4.4
	542	4.0
	543	1.6
	544	1.2
	545	4.2
	546	5.6
	547	8.8
	548	6.4
	549	3.2
	550	1.6
	551	4.8
	552	10.4
	553	6.2
	554	3.6
	555	4.0
	556	13.6
	557	4.0
	558	3.6
	559	4.0
	560	7.2
	561	4.8
	562	3.2
	563	4.0
	564	7.2
	565	5.0
	566	5.0
	567	3.6
	568	6.8
	569	5.6
	570	1.6
	571	7.2
	572	12.4

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	573	3.2
	574	2.8
	575	4.4
	na	15.0
	576	6.8
	577	7.6
	578	5.3
	579	5.2
	580	4.9
	581	4.6
	582	3.8
	583	2.3
	584	1.5
	585	2.3
	586	2.5
	587	2.3
	588	7.6
	589	4.0
	590	3.8
	591	4.3
	592	7.4
	593	2.9
	594	12.3
	595	4.6
	596	3.8
	597	3.8
	598	4.6
	599	3.8
	600	3.8
	601	5.9
	602	4.6
	603	9.4
	604	4.6
	605	7.2
	606	3.4
	607	2.1
	608	3.0
	609	2.1
	610	2.7
	611	4.9
	612	2.1
	613	1.9
	614	1.1
	615	4.6
	616	2.5
	617	1.5
	618	2.3
	619	5.3
	620	2.9
	621	3.8
	622	9.0
	623	3.0
	624	6.5
	625	5.3
	626	4.3
	627	4.3
	628	5.3
	629	4.6
	630	3.3
	631	4.4
	632	4.6
	633	3.8
	634	2.1
	635	5.3
	636	4.3
	637	4.3
	638	2.7
	639	3.4
	640	5.7
	641	4.2
	642	2.7
	643	3.0

RHYTHMITE THICKNESS
AGASSIZ SEQUENCE IN LAKE WINNIPEG NORTH BASIN

Core 96-900-205	Core 96-900-206	
	644	2.7
	645	1.7
	646	2.3
	647	2.7
	648	3.0
	649	3.4
	650	5.2
	651	4.2
	652	3.3
	653	1.9
	654	3.8
	655	5.1
	656	6.8
	657	5.1
	658	9.3
	659	8.4
	660	8.9
	661	3.8
	662	8.4
	663	4.6
	664	5.5
	665	15.0
	666	6.8
	667	3.4
	668	3.6
	669	6.8
	670	3.4
	671	3.2
	672	5.1
	673	2.1
	674	3.8
	675	10.1
	676	8.4
	677	7.6
	678	5.3
	679	5.9
	680	6.8
	681	8.0
	682	8.4
	683	7.0
	684	1.7
	685	2.5
	686	5.5
	687	5.8
	688	4.7
	689	8.6
	690	4.9
	691	10.7
	692	9.1
	693	10.5
	694	8.2
	695	5.8
	696	5.6
	697	4.5
	698	5.8
	699	9.5
	700	7.8
	701	8.2
	702	9.1
	703	4.5
	704	3.7
	705	10.3
	706	11.1
	707	5.1
	708	10.7
	709	15.7

Appendix 10.11

Lake Winnipeg ice scour data

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1. WMC International Limited
2. Geological Survey of Canada, Ottawa
3. Geological Survey of Canada (Atlantic)

During the 1994 and 1996 Lake Winnipeg surveys, side scan sonar data were collected on Lake Winnipeg (Todd et al., 1998). Features present on the records subsequently were categorized, measured, and mapped in order to address their distribution, character, and origin. Particular emphasis was placed on linear features in order to test for and determine the extent of ice scour. Results of the 1994 survey were summarized by McKinnon (1996) and McKinnon et al. (1996). Subsequently, features from the 1996 survey were examined, and raw data are presented here.

Small-scale bathymetric features in both the North and South Basins are dominated by two categories of linear features preferentially oriented north-northwest to south-southeast. The first type, referred to as scours, exhibits multiple grooves up to 200 m wide and several kilometres long, and are apparent on high frequency seismic records as grooves up to 0.95 m deep. The second type, referred to as LABAs (Linear Acoustic Backscatter Anomalies), consist of single, ~15 m wide dark bands on the side scan records, several hundred metres long, with diffuse lateral boundaries. No relief indicated by seismic profiles of the latter type, although the features are associated with a strong seismic signal often masking underlying reflectors.

The linear features are attributed to scour by pressure ridges formed in ice, on the basis of their geometry, distribution, and orientation, and on the basis of knowledge of pressure ridge formation, and analogy to other areas. Prevailing wind directions in the area correlate to the scour orientation, suggesting that wind is a major control on the orientation and distribution of the features. Other factors influencing their distribution are water depth and lake floor relief.

Other features noted were flow-parallel bedforms, flow-transverse bedforms, bedrock outcrop, and eroded outcrop of Lake Agassiz sediments.

The data appendix is structured as follows. Due to variations in procedure, "na" is indicated where a variable was not observed.

1. Row number
2. Year: 1994 or 1996
3. Basin: South or North
4. Line: geophysical survey line number
5. Day: day number as recorded in navigation files
6. Time: time of observation as recorded in navigation files
7. Lat: NAD83 latitude
8. Long: NAD83 longitude
9. Type: scour or LABA
10. Orient: orientation from true north, corrected for lateral exaggeration on the sonar records
11. Width: width of the feature in metres, arbitrarily set to 1 if "na"
12. Keel: multiple or single
13. Strength: strength of development; very fresh, fresh, moderately fresh, moderately faint, faint, very faint, moderately buried, buried, very buried
14. Reflector: strength of seismic reflector: none, weak, moderate, strong

15. Comment: range or orientation, cross-cutting, berms and furrows, plan-view geometry, terminations, Lake Agassiz sediments

REFERENCES

McKinnon, N. T.
1996. Mapping of lakefloor features in Lake Winnipeg using sidescan sonar and high resolution seismic reflection; Carleton University B.Sc. thesis, 41 p.

McKinnon, N. T., Todd, B. J. and Lewis, C. F. M.
1996. Mapping of linear features on the Lake Winnipeg lakefloor; Geological Association of Canada Program with Abstracts, v. 21, p. 64.

Todd, B. J., Lewis, C. F. M., Nielsen, E., Thorleifson, L. H., Bezys, R. K. and Weber, W.
1998. Lake Winnipeg: geological setting and sediment seismostratigraphy; Journal of Paleolimnology, v. 19, p. 215-244.

Format for side-scan sonar observations:

Year

- 1994
- 1996

Basin

- South
- North

Line

- 3 to 19

Day

- e.g. 220

Time

- e.g. 1623; to the nearest minute with half minutes rounded down

Latitude

- e.g. 50.4852; rounded to 0.0001°

Longitude

- e.g. 96.8334; rounded to 0.0001°

Type

- scour
- LABA

Orientation

- in degrees, to the nearest degree

Width

- from 1 to 250 m; blank fields related to narrow features assigned a value of 1

Keel

- single
- multiple

Strength of development; faint refers to sidescan observations (1996); buried refers to seistec observations (1994)

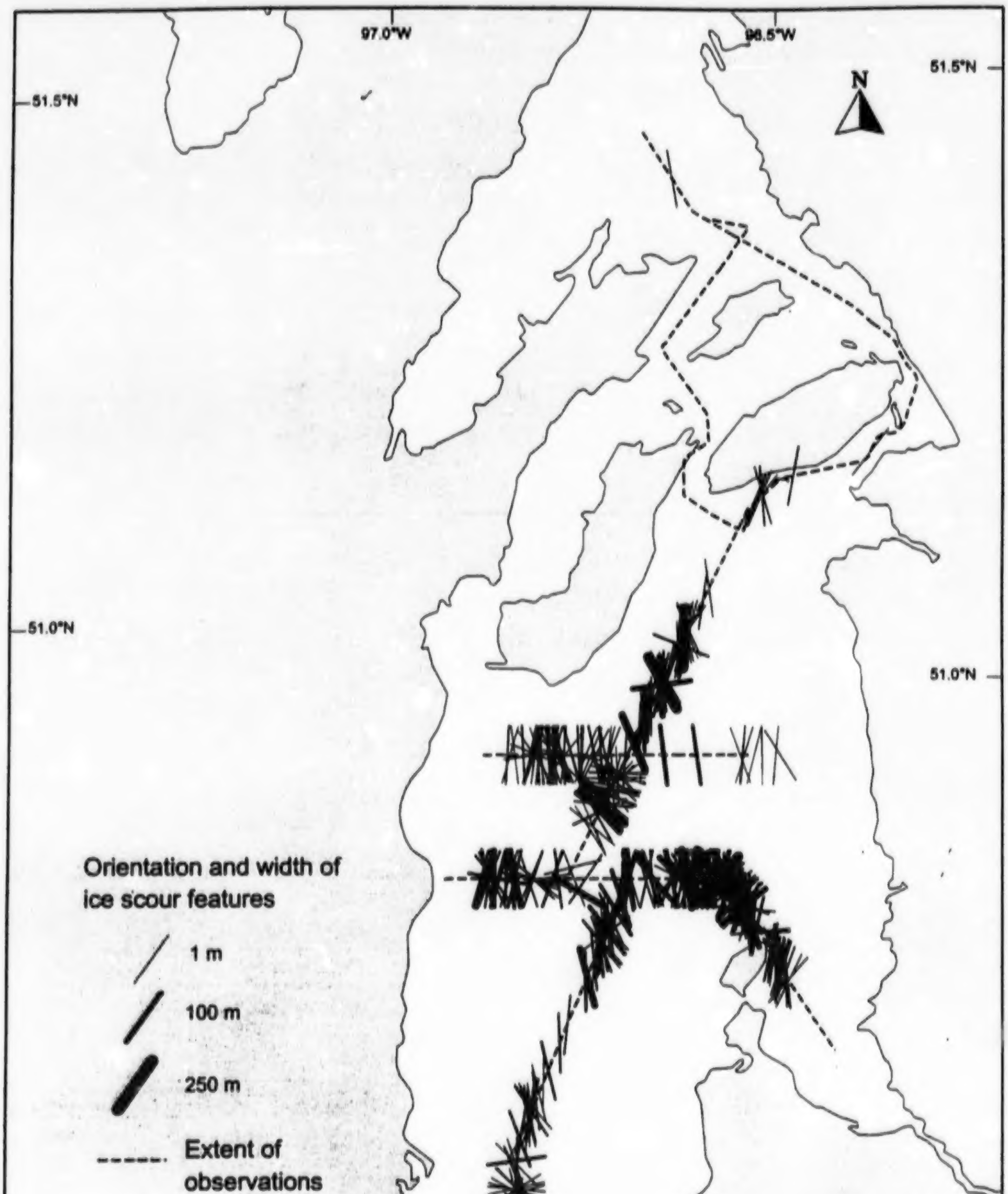
- very fresh
- fresh
- moderately fresh
- moderately faint
- faint
- very faint
- moderately buried
- buried
- very buried

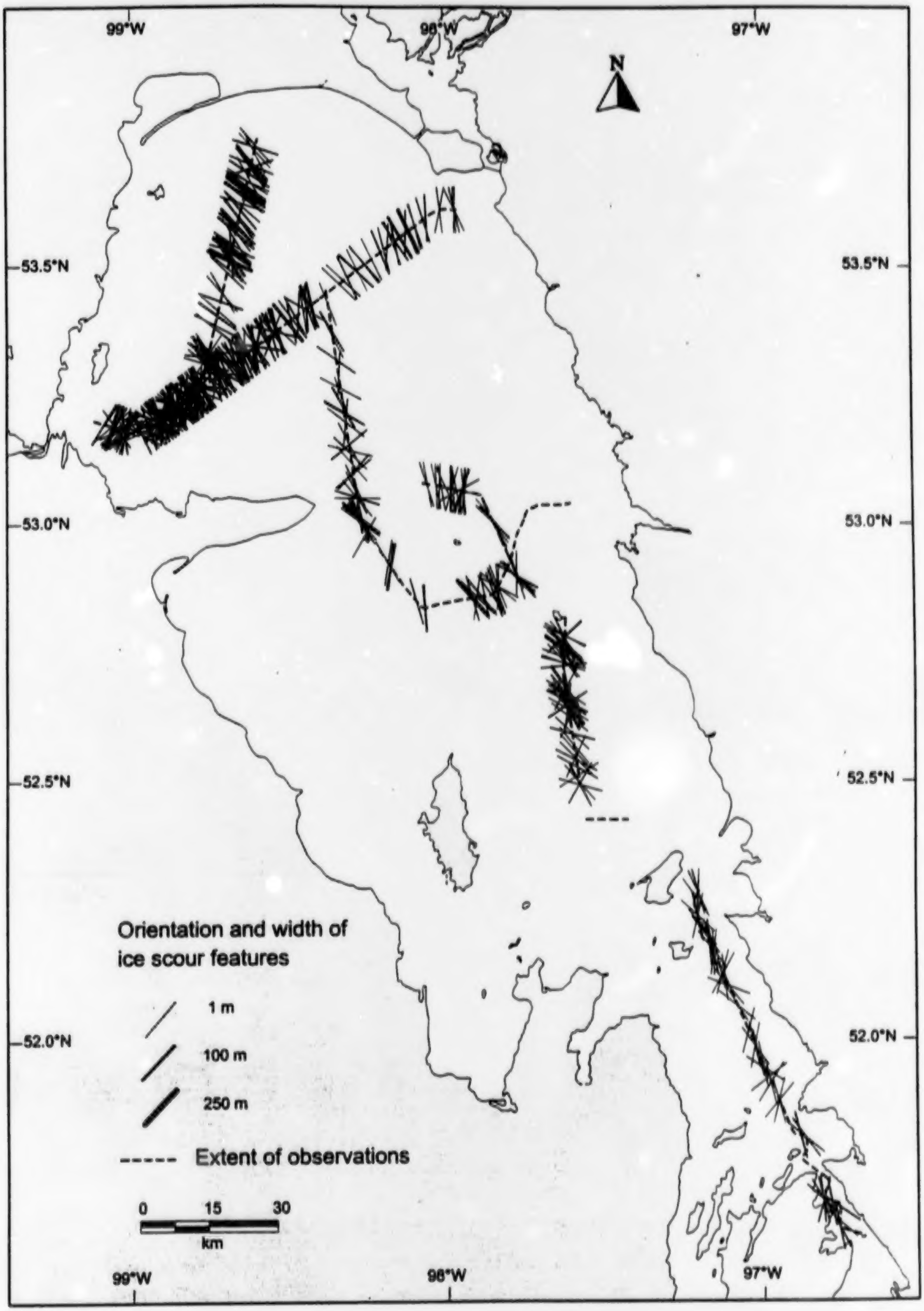
Reflector character

- none
- weak
- moderate
- strong

Comment

- range of orientation
- cross-cutting
- berms and furrows
- plan-view geometry
- terminations
- Lake Agassiz sediments


97.0°W
96.5°W
51.5°N
51.0°N
50.5°N
N
Orientation and width of ice scour features
1 m
100 m
250 m
Extent of observations
0
10
20
km


99°W
98°W
97°W
N
53.5°N
53.0°N
52.5°N
52.0°N
Orientation and width of ice scour features
1 m
100 m
250 m
Extent of observations
0
15
30
km

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
1	1994	S	3	220	1623	50.4852	96.8334	scour	232	1	na	na	na	na
2	1994	S	3	220	1624	50.4862	96.8334	scour	268	1	na	na	na	232 and 268 are younger
3	1994	S	3	220	1624	50.4862	96.8334	scour	354	1	na	na	na	complex cross cutting scour
4	1994	S	3	220	1625	50.4872	96.8334	scour	229	1	na	na	na	na
5	1994	S	3	220	1626	50.4881	96.8334	scour	332	1	na	na	na	complex with 229 as youngest
6	1994	S	3	220	1627	50.4891	96.8334	scour	348	1	na	na	na	na
7	1994	S	3	220	1628	50.4901	96.8334	scour	186	1	na	na	na	na
8	1994	S	3	220	1629	50.4911	96.8334	LABA	276	30	na	na	na	na
9	1994	S	3	220	1631	50.4931	96.8334	scour	348	1	na	na	na	na
10	1994	S	3	220	1631	50.4931	96.8334	scour	240	1	na	na	na	complex
11	1994	S	3	220	1631	50.4931	96.8334	scour	195	1	na	na	na	na
12	1994	S	3	220	1632	50.4941	96.8334	scour	206	1	na	na	na	na
13	1994	S	3	220	1633	50.4951	96.8334	scour	327	100	multiple	na	na	complex
14	1994	S	3	220	1635	50.4970	96.8333	scour	227	1	na	na	na	na
15	1994	S	3	220	1639	50.5010	96.8334	scour	340	1	na	na	na	na
16	1994	S	3	220	1645	50.5069	96.8333	scour	305	1	na	na	na	na
17	1994	S	3	220	1650	50.5119	96.8334	scour	343	1	single	na	na	single keel and older
18	1994	S	3	220	1650	50.5119	96.8334	scour	234	1	na	na	na	na
19	1994	S	3	220	1652	50.5139	96.8334	scour	180	1	multiple	na	na	na
20	1994	S	3	220	1652	50.5139	96.8334	scour	206	1	multiple	na	na	na
21	1994	S	3	220	1659	50.5203	96.8334	scour	316	1	na	na	na	na
22	1994	S	3	220	1659	50.5203	96.8334	scour	337	1	na	na	na	zig-zag younger
23	1994	S	3	220	1701	50.5222	96.8334	scour	312	1	na	na	na	na
24	1994	S	3	220	1701	50.5222	96.8334	scour	185	1	multiple	na	na	non-linear
25	1994	S	3	220	1706	50.5267	96.8332	scour	189	1	multiple	na	na	na
26	1994	S	3	220	1708	50.5285	96.8333	scour	342	1	na	na	na	na
27	1994	S	3	220	1708	50.5285	96.8333	scour	346	1	na	na	na	parallels track to 1716
28	1994	S	3	220	1714	50.5341	96.8334	scour	345	1	na	na	na	na
29	1994	S	3	220	1714	50.5341	96.8334	scour	191	15	multiple	faint	na	na
30	1994	S	3	220	1715	50.5350	96.8333	scour	193	1	na	na	na	na
31	1994	S	3	220	1717	50.5369	96.8333	scour	340	150	na	na	na	complex cross cutting scour
32	1994	S	3	220	1718	50.5378	96.8333	scour	314	1	na	na	na	na
33	1994	S	3	220	1720	50.5396	96.8333	scour	201	1	na	na	na	na
34	1994	S	3	220	1721	50.5406	96.8333	scour	306	1	na	na	na	na
35	1994	S	3	220	1730	50.5489	96.8333	scour	301	1	na	na	na	na
36	1994	S	3	220	1732	50.5505	96.8332	scour	346	1	multiple	na	na	na
37	1994	S	3	220	1735	50.5537	96.8334	scour	215	1	na	na	na	na
38	1994	S	3	220	1735	50.5537	96.8334	scour	192	1	multiple	na	na	na
39	1994	S	3	220	1735	50.5537	96.8334	scour	182	1	na	na	na	na
40	1994	S	3	220	1737	50.5557	96.8334	scour	336	1	multiple	na	na	na
41	1994	S	3	220	1737	50.5557	96.8334	scour	180	1	na	na	na	na
42	1994	S	3	220	1746	50.5641	96.8333	scour	192	1	na	na	na	na
43	1994	S	3	220	1750	50.5679	96.8333	scour	357	1	multiple	na	na	na
44	1994	S	3	220	1755	50.5724	96.8332	scour	346	1	na	faint	na	na
45	1994	S	3	220	1759	50.5753	96.8333	scour	254	1	na	na	na	stops and goes back out
46	1994	S	3	220	1801	50.5759	96.8333	scour	255	1	multiple	faint	na	na
47	1994	S	3	220	1801	50.5759	96.8333	scour	300	1	na	na	na	na
48	1994	S	3	220	1804	50.5774	96.8334	scour	285	1	na	na	na	na
49	1994	S	3	220	1805	50.5782	96.8334	scour	238	1	multiple	faint	na	na
50	1994	S	3	220	1806	50.5787	96.8335	scour	275	1	na	na	na	na
51	1994	S	3	220	1809	50.5792	96.8335	scour	258	1	multiple	na	na	na
52	1994	S	3	220	1809	50.5792	96.8335	scour	313	1	multiple	na	na	na
53	1994	S	3	220	1811	50.5799	96.8336	scour	315	1	na	faint	na	na
54	1994	S	3	220	1820	50.5878	96.8333	scour	338	15	multiple	na	na	na
55	1994	S	3	220	1825	50.5925	96.8333	LABA	334	1	na	na	strong	na
56	1994	S	3	220	1830	50.5972	96.8333	scour	341	1	na	na	na	na
57	1994	S	3	220	1830	50.5972	96.8333	scour	180	1	multiple	faint	na	narrow
58	1994	S	3	220	1832	50.5991	96.8335	scour	315	1	na	na	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
59	1994	S	3	220	1835	50.6019	96.8333	scour	262	50	multiple	na	na	na
60	1994	S	3	220	1855	50.6199	96.8291	scour	208	1	na	na	na	na
61	1994	S	3	220	1855	50.6199	96.8291	scour	339	40	multiple	na	na	furrows
62	1994	S	3	220	1858	50.6224	96.8273	scour	189	30	na	na	na	keel looks laba-like ~15m
63	1994	S	3	220	1912	50.6347	96.8192	scour	183	1	na	na	na	na
64	1994	S	3	220	1913	50.6356	96.8187	scour	191	1	multiple	na	na	na
65	1994	S	3	220	1914	50.6365	96.8180	scour	345	1	na	na	na	na
66	1994	S	3	220	1915	50.6373	96.8174	scour	358	1	na	na	na	na
67	1994	S	3	220	1918	50.6400	96.8157	scour	348	1	multiple	na	na	na
68	1994	S	3	220	1920	50.6417	96.8146	scour	353	1	na	na	na	na
69	1994	S	3	220	1921	50.6426	96.8141	scour	191	1	na	na	na	na
70	1994	S	3	220	1921	50.6426	96.8141	LABA	326	25	na	na	strong	na
71	1994	S	3	220	1922	50.6435	96.8134	scour	189	100	na	na	na	na
72	1994	S	3	220	1923	50.6444	96.8128	scour	332	1	na	na	na	na
73	1994	S	3	220	1924	50.6452	96.8123	scour	192	1	na	na	na	na
74	1994	S	3	220	1925	50.6461	96.8117	scour	320	1	na	na	na	na
75	1994	S	3	220	1931	50.6513	96.8082	LABA	353	15	na	buried	na	na
76	1994	S	3	220	1938	50.6574	96.8042	scour	346	1	multiple	faint	na	na
77	1994	S	3	220	1948	50.6660	96.7985	scour	181	1	na	faint	na	narrow
78	1994	S	3	220	1959	50.6758	96.7921	scour	346	40	multiple	buried	na	na
79	1994	S	3	220	2025	50.6963	96.7774	LABA	358	30	na	na	strong	long
80	1994	S	3	220	2042	50.7131	96.7673	scour	186	16	multiple	na	na	na
81	1994	S	3	220	2123	50.7488	96.7437	scour	359	45	multiple	very faint	na	deep on seismic
82	1994	S	3	220	2127	50.7523	96.7413	scour	345	125	multiple	buried	na	coarser sediment
83	1994	S	3	220	2142	50.7654	96.7326	scour	354	20	multiple	na	na	na
84	1994	S	3	220	2145	50.7681	96.7309	scour	186	20	multiple	na	na	na
85	1994	S	3	220	2155	50.7768	96.7251	scour	353	50	multiple	faint	na	na
86	1994	S	3	220	2155	50.7768	96.7251	scour	186	40	multiple	fresh	na	na
87	1994	S	3	220	2158	50.7794	96.7233	scour	340	25	multiple	na	na	na
88	1994	S	3	220	2158	50.7794	96.7233	scour	321	16	multiple	faint	na	na
89	1994	S	3	220	2159	50.7803	96.7228	scour	187	100	na	fresh	na	na
90	1994	S	3	220	2200	50.7812	96.7222	scour	349	25	multiple	fresh	na	na
91	1994	S	3	220	2200	50.7812	96.7222	scour	318	30	multiple	na	na	na
92	1994	S	3	220	2204	50.7847	96.7198	scour	354	1	na	na	na	non-linear
93	1994	S	3	220	2208	50.7882	96.7175	scour	234	10	single	na	na	na
94	1994	S	3	220	2208	50.7882	96.7175	scour	195	1	single	faint	na	na
95	1994	S	3	220	2211	50.7908	96.7158	scour	323	75	multiple	faint	na	na
96	1994	S	3	220	2213	50.7925	96.7146	scour	317	16	multiple	fresh	na	na
97	1994	S	3	220	2213	50.7925	96.7146	scour	348	15	multiple	faint	na	na
98	1994	S	3	220	2214	50.7934	96.7140	scour	358	1	na	faint	na	na
99	1994	S	3	220	2215	50.7943	96.7134	scour	350	1	na	faint	na	na
100	1994	S	3	220	2219	50.7978	96.7110	scour	196	10	single	faint	na	na
101	1994	S	3	220	2221	50.7996	96.7099	LABA	335	20	na	na	strong	has relief
102	1994	S	3	220	2230	50.8076	96.7047	scour	202	120	multiple	fresh	na	parallel to track, 2226-2245
103	1994	S	3	220	2230	50.8076	96.7047	scour	328	70	na	na	na	curved, from 355-253
104	1994	S	3	220	2232	50.8092	96.7033	scour	188	16	multiple	faint	na	na
105	1994	S	3	220	2241	50.8173	96.6981	scour	342	80	multiple	na	na	na
106	1994	S	3	220	2248	50.8223	96.6935	scour	359	90	multiple	fresh	na	na
107	1994	S	3	220	2256	50.8306	96.6893	scour	349	30	multiple	na	na	light band
108	1994	S	3	220	2257	50.8314	96.6886	scour	195	80	multiple	na	na	na
109	1994	S	3	220	2259	50.8333	96.6876	scour	350	80	multiple	na	na	na
110	1994	S	4	221	1538	50.8334	96.8815	LABA	196	15	single	mod buried	none	na
111	1994	S	4	221	1542	50.8333	96.8755	scour	198	120	multiple	fresh	na	furrows
112	1994	S	4	221	1544	50.8333	96.8726	scour	349	50	multiple	na	na	na
113	1994	S	4	221	1546	50.8333	96.8695	scour	189	20	multiple	faint	na	na
114	1994	S	4	221	1546	50.8333	96.8695	LABA	201	20	na	na	na	3 features on one channel
115	1994	S	4	221	1548	50.8333	96.8666	LABA	334	15	single	na	na	na
116	1994	S	4	221	1548	50.8333	96.8666	scour	357	15	multiple	faint	na	short

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
117	1994	S	4	221	1549	50.8334	96.8651	scour	359	16	multiple	na	na	na
118	1994	S	4	221	1549	50.8334	96.8651	scour	323	25	multiple	faint	na	na
119	1994	S	4	221	1551	50.8334	96.8621	LABA	180	20	single	na	moderate	na
120	1994	S	4	221	1553	50.8334	96.8590	scour	281	50	multiple	fresh	na	na
121	1994	S	4	221	1554	50.8334	96.8576	scour	195	75	multiple	na	na	furrows
122	1994	S	4	221	1600	50.8334	96.8485	LABA	181	15	na	na	strong	na
123	1994	S	4	221	1601	50.8333	96.8471	LABA	183	15	na	na	strong	na
124	1994	S	4	221	1603	50.8333	96.8441	scour	197	10	single	mod fresh	na	na
125	1994	S	4	221	1606	50.8333	96.8396	scour	356	60	multiple	na	na	na
126	1994	S	4	221	1606	50.8333	96.8396	scour	345	10	multiple	na	na	na
127	1994	S	4	221	1607	50.8333	96.8381	scour	347	60	multiple	na	na	laba-like
128	1994	S	4	221	1608	50.8333	96.8366	scour	193	40	multiple	na	na	laba-like scours on ss
129	1994	S	4	221	1610	50.8333	96.8335	scour	349	30	multiple	fresh	na	na
130	1994	S	4	221	1610	50.8333	96.8335	scour	350	10	single	na	na	na
131	1994	S	4	221	1620	50.8333	96.8186	scour	342	16	multiple	faint	na	na
132	1994	S	4	221	1622	50.8333	96.8157	LABA	283	20	single	na	na	na
133	1994	S	4	221	1622	50.8333	96.8157	scour	203	20	multiple	mod fresh	na	na
134	1994	S	4	221	1623	50.8333	96.8142	LABA	292	13	multiple	na	na	na
135	1994	S	4	221	1624	50.8332	96.8126	scour	199	30	multiple	fresh	na	na
136	1994	S	4	221	1624	50.8332	96.8126	scour	313	16	multiple	fresh	na	na
137	1994	S	4	221	1624	50.8332	96.8126	scour	279	10	multiple	mod faint	na	na
138	1994	S	4	221	1626	50.8333	96.8097	scour	309	16	multiple	fresh	na	na
139	1994	S	4	221	1633	50.8333	96.7992	scour	260	16	single	faint	na	na
140	1994	S	4	221	1641	50.8333	96.7872	scour	200	46	multiple	fresh	na	furrows
141	1994	S	4	221	1646	50.8333	96.7798	scour	353	32	multiple	faint	na	na
142	1994	S	4	221	1700	50.8333	96.7588	scour	339	10	single	na	na	berms
143	1994	S	4	221	1710	50.8332	96.7440	scour	214	20	multiple	buried	moderate	na
144	1994	S	4	221	1749	50.8332	96.6856	scour	354	72	multiple	mod fresh	na	na
145	1994	S	4	221	1749	50.8332	96.6856	scour	190	16	multiple	faint	na	na
146	1994	S	4	221	1750	50.8333	96.6843	scour	344	7	single	faint	na	na
147	1994	S	4	221	1802	50.8331	96.6660	LABA	343	12	na	buried	na	berms
148	1994	S	4	221	1803	50.8332	96.6645	LABA	192	20	na	buried	na	na
149	1994	S	4	221	1806	50.8333	96.6599	LABA	338	16	na	na	moderate	na
150	1994	S	4	221	1806	50.8333	96.6599	LABA	344	16	na	na	moderate	na
151	1994	S	4	221	1808	50.8333	96.6568	scour	355	10	single	faint	na	na
152	1994	S	4	221	1809	50.8334	96.6552	scour	320	80	multiple	na	na	sharp
153	1994	S	4	221	1809	50.8334	96.6552	scour	340	8	single	faint	na	na
154	1994	S	4	221	1824	50.8334	96.6320	scour	348	30	multiple	fresh	na	na
155	1994	S	4	221	1824	50.8334	96.6320	scour	345	30	multiple	fresh	na	na
156	1994	S	4	221	1824	50.8334	96.6320	scour	352	20	multiple	fresh	na	na
157	1994	S	4	221	1824	50.8334	96.6320	scour	216	40	na	fresh	na	wavy
158	1994	S	4	221	1825	50.8334	96.6307	scour	205	40	multiple	very faint	na	na
159	1994	S	4	221	1827	50.8335	96.6276	scour	181	16	multiple	faint	na	na
160	1994	S	4	221	1829	50.8335	96.6245	scour	191	16	multiple	buried	na	na
161	1994	S	4	221	1831	50.8334	96.6211	scour	331	8	single	na	na	short
162	1994	S	4	221	1831	50.8334	96.6211	scour	316	110	multiple	na	na	turns abruptly to 287
163	1994	S	4	221	1832	50.8333	96.6198	scour	297	10	single	faint	na	na
164	1994	S	4	221	1833	50.8333	96.6183	scour	191	20	multiple	faint	na	na
165	1994	S	4	221	1833	50.8333	96.6183	scour	352	10	single	faint	na	na
166	1994	S	4	221	1834	50.8334	96.6166	scour	326	1	na	na	na	non-linear
167	1994	S	4	221	1835	50.8334	96.6150	scour	183	14	multiple	faint	na	na
168	1994	S	4	221	1835	50.8334	96.6150	LABA	347	45	na	na	strong	na
169	1994	S	4	221	1836	50.8334	96.6135	scour	184	16	multiple	na	na	na
170	1994	S	4	221	1837	50.8334	96.6120	scour	350	140	multiple	fresh	na	na
171	1994	S	4	221	1838	50.8334	96.6106	scour	327	20	multiple	very faint	na	cross-cut by 256
172	1994	S	4	221	1838	50.8334	96.6106	scour	354	1	na	faint	na	na
173	1994	S	4	221	1838	50.8334	96.6106	scour	347	8	single	faint	na	na
174	1994	S	4	221	1838	50.8334	96.6106	scour	195	1	multiple	na	na	laba-like

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
175	1994	S	4	221	1839	50.8334	96.6090	scour	216	16	multiple	na	na	na
176	1994	S	4	221	1840	50.8333	96.6073	scour	338	80	multiple	na	na	na
177	1994	S	4	221	1840	50.8333	96.6073	scour	334	50	multiple	faint	na	na
178	1994	S	4	221	1842	50.8335	96.6042	scour	203	16	multiple	na	na	na
179	1994	S	4	221	1843	50.8336	96.6026	scour	185	140	multiple	na	na	laba-like
180	1994	S	4	221	1845	50.8334	96.5996	scour	349	25	multiple	fresh	na	na
181	1994	S	4	221	1846	50.8334	96.5979	LABA	181	45	multiple	na	na	na
182	1994	S	4	221	1847	50.8334	96.5963	scour	329	10	multiple	faint	na	na
183	1994	S	4	221	1847	50.8334	96.5963	LABA	343	1	single	very faint	na	na
184	1994	S	4	221	1847	50.8334	96.5963	scour	196	16	multiple	faint	na	na
185	1994	S	4	221	1850	50.8333	96.5913	scour	354	10	single	na	na	na
186	1994	S	4	221	1850	50.8333	96.5913	scour	343	30	multiple	faint	na	na
187	1994	S	4	221	1850	50.8333	96.5913	scour	305	60	multiple	very faint	na	na
188	1994	S	4	221	1850	50.8333	96.5913	scour	359	16	multiple	na	na	na
189	1994	S	4	221	1850	50.8333	96.5913	scour	344	10	na	very faint	na	na
190	1994	S	4	221	1853	50.8333	96.5867	scour	314	90	multiple	very fresh	na	na
191	1994	S	4	221	1853	50.8333	96.5867	scour	203	20	single	na	na	na
192	1994	S	4	221	1853	50.8333	96.5867	scour	188	50	multiple	na	na	na
193	1994	S	4	221	1855	50.8336	96.5835	scour	348	15	multiple	na	na	na
194	1994	S	4	221	1855	50.8336	96.5835	scour	199	10	single	na	na	na
195	1994	S	4	221	1855	50.8336	96.5835	scour	202	1	multiple	na	na	na
196	1994	S	4	221	1858	50.8335	96.5787	LABA	181	1	na	na	na	in other scours
197	1994	S	4	221	1859	50.8334	96.5771	LABA	184	1	na	na	na	in other scour
198	1994	S	4	221	1900	50.8333	96.5755	scour	183	30	na	na	na	na
199	1994	S	4	221	1900	50.8333	96.5755	scour	183	30	multiple	na	na	cross-cut by 185
200	1994	S	4	221	1900	50.8333	96.5755	scour	276	200	multiple	na	na	non-linear
201	1994	S	4	221	1900	50.8333	96.5755	scour	283	200	multiple	na	na	>200 m wide, curves to 307
202	1994	S	4	221	1901	50.8332	96.5739	LABA	187	1	na	na	na	in other scour
203	1994	S	4	221	1902	50.8333	96.5723	LABA	183	1	na	na	na	in other scour
204	1994	S	4	221	1918	50.8382	96.5744	LABA	276	30	na	na	na	subparallel to scour
205	1994	S	4	221	1918	50.8382	96.5744	scour	270	15	multiple	fresh	na	na
206	1994	S	4	221	1920	50.8368	96.5757	scour	326	150	multiple	na	na	non-linear
207	1994	S	4	221	1925	50.8336	96.5719	scour	203	80	multiple	fresh	na	na
208	1994	S	4	221	1926	50.8335	96.5704	scour	238	15	multiple	na	na	cross-cut by large feature
209	1994	S	4	221	1926	50.8335	96.5704	scour	198	30	multiple	fresh	na	na
210	1994	S	4	221	1926	50.8335	96.5704	scour	222	20	multiple	na	na	cross-cut by large feature
211	1994	S	4	221	1926	50.8335	96.5704	scour	221	200	multiple	fresh	na	large, non-linear 310-180-285
212	1994	S	4	221	1927	50.8334	96.5689	scour	355	15	multiple	fresh	na	na
213	1994	S	4	221	1927	50.8334	96.5689	LABA	350	20	na	na	na	non-linear, cross-cut by scour
214	1994	S	4	221	1927	50.8334	96.5689	scour	349	20	multiple	fresh	na	non-linear
215	1994	S	4	221	1930	50.8316	96.5658	scour	316	20	multiple	fresh	na	na
216	1994	S	4	221	1930	50.8316	96.5658	scour	307	30	multiple	fresh	na	na
217	1994	S	4	221	1931	50.8307	96.5652	scour	182	15	multiple	buried	na	na
218	1994	S	4	221	1932	50.8299	96.5645	scour	296	50	multiple	fresh	na	non-linear, 308-354
219	1994	S	4	221	1932	50.8299	96.5645	scour	269	50	multiple	fresh	na	na
220	1994	S	4	221	1934	50.8285	96.5629	LABA	343	25	single	na	na	na
221	1994	S	4	221	1934	50.8285	96.5629	LABA	188	20	single	fresh	na	na
222	1994	S	4	221	1936	50.8271	96.5611	scour	346	50	multiple	fresh	na	na
223	1994	S	4	221	1936	50.8271	96.5611	scour	347	20	multiple	mod fresh	na	na
224	1994	S	4	221	1938	50.8258	96.5592	scour	347	20	multiple	faint	na	na
225	1994	S	4	221	1940	50.8241	96.5569	scour	346	60	multiple	fresh	na	na
226	1994	S	4	221	1940	50.8241	96.5569	scour	205	50	multiple	fresh	na	na
227	1994	S	4	221	1940	50.8241	96.5569	scour	229	20	multiple	faint	na	na
228	1994	S	4	221	1942	50.8225	96.5547	LABA	344	16	single	faint	na	na
229	1994	S	4	221	1944	50.8210	96.5528	scour	183	30	multiple	mod fresh	na	na
230	1994	S	4	221	1944	50.8210	96.5528	scour	349	20	multiple	mod fresh	na	na
231	1994	S	4	221	1945	50.8203	96.5519	scour	349	100	multiple	na	na	furrows
232	1994	S	4	221	1946	50.8198	96.5512	LABA	354	10	single	mod fresh	weak	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
233	1994	S	4	221	1946	50.8198	96.5512	LABA	193	18	single	mod fresh	weak	na
234	1994	S	4	221	1947	50.8191	96.5502	LABA	353	10	single	mod fresh	weak	na
235	1994	S	4	221	1948	50.8189	96.5499	LABA	197	10	single	mod fresh	weak	na
236	1994	S	4	221	1949	50.8187	96.5497	scour	359	10	multiple	faint	na	na
237	1994	S	4	221	1950	50.8178	96.5485	scour	221	30	multiple	mod fresh	na	na
238	1994	S	4	221	1951	50.8160	96.5461	scour	186	80	multiple	fresh	na	na
239	1994	S	4	221	1951	50.8160	96.5461	scour	223	40	multiple	mod fresh	na	na
240	1994	S	4	221	1954	50.8144	96.5439	scour	350	40	multiple	buried	na	na
241	1994	S	4	221	1954	50.8144	96.5439	scour	343	10	single	buried	na	na
242	1994	S	4	221	1956	50.8131	96.5421	scour	198	15	single	na	na	na
243	1994	S	4	221	1956	50.8131	96.5421	scour	291	35	multiple	mod buried	na	na
244	1994	S	4	221	1956	50.8131	96.5421	scour	357	10	single	buried	na	na
245	1994	S	4	221	1956	50.8131	96.5421	scour	337	10	single	buried	na	na
246	1994	S	4	221	1957	50.8125	96.5413	scour	197	15	single	very faint	na	na
247	1994	S	4	221	1957	50.8125	96.5413	scour	225	30	multiple	faint	na	na
248	1994	S	4	221	1958	50.8113	96.5398	scour	220	40	multiple	mod fresh	na	na
249	1994	S	4	221	1958	50.8113	96.5398	scour	231	40	multiple	mod fresh	na	na
250	1994	S	4	221	1958	50.8113	96.5398	scour	350	16	multiple	fresh	na	na
251	1994	S	4	221	1959	50.8101	96.5382	scour	230	40	multiple	mod fresh	na	na
252	1994	S	4	221	1959	50.8101	96.5382	scour	341	15	multiple	fresh	na	cross-cuts 1959 and 1958
253	1994	S	4	221	2000	50.8091	96.5370	LABA	341	15	single	mod fresh	na	na
254	1994	S	4	221	2000	50.8091	96.5370	LABA	230	30	single	mod fresh	moderate	na
255	1994	S	4	221	2000	50.8091	96.5370	scour	209	10	multiple	mod fresh	na	na
256	1994	S	4	221	2001	50.8084	96.5360	scour	359	20	multiple	mod fresh	na	na
257	1994	S	4	221	2001	50.8084	96.5360	scour	275	15	multiple	very faint	na	na
258	1994	S	4	221	2001	50.8084	96.5360	scour	347	10	multiple	very faint	na	na
259	1994	S	4	221	2002	50.8076	96.5351	scour	344	45	multiple	fresh	na	furrows
260	1994	S	4	221	2002	50.8076	96.5351	scour	344	60	multiple	fresh	na	ends on records
261	1994	S	4	221	2005	50.8052	96.5323	scour	345	5	single	very buried	na	na
262	1994	S	4	221	2005	50.8052	96.5323	scour	198	16	multiple	very buried	na	na
263	1994	S	4	221	2006	50.8042	96.5309	scour	181	30	multiple	mod fresh	na	na
264	1994	S	4	221	2010	50.8012	96.5279	scour	349	15	single	buried	na	na
265	1994	S	4	221	2011	50.8004	96.5270	scour	344	40	multiple	na	na	na
266	1994	S	4	221	2012	50.7996	96.5261	scour	185	60	multiple	mod fresh	na	na
267	1994	S	4	221	2012	50.7996	96.5261	scour	349	40	multiple	faint	na	na
268	1994	S	4	221	2015	50.7972	96.5234	LABA	310	15	single	faint	na	non-linear, 334-360
269	1994	S	4	221	2018	50.7948	96.5206	scour	193	40	multiple	na	na	na
270	1994	S	4	221	2019	50.7939	96.5201	LABA	191	15	single	faint	na	na
271	1994	S	4	221	2020	50.7931	96.5195	scour	310	5	single	very faint	na	na
272	1994	S	4	221	2024	50.7897	96.5167	LABA	264	15	multiple	mod fresh	strong	na
273	1994	S	4	221	2025	50.7888	96.5160	scour	268	10	multiple	buried	na	na
274	1994	S	4	221	2043	50.7728	96.5033	LABA	193	30	single	faint	strong	na
275	1994	S	4	221	2044	50.7719	96.5026	LABA	186	10	single	faint	na	na
276	1994	S	4	221	2046	50.7703	96.5014	scour	344	5	single	very faint	na	na
277	1994	S	4	221	2048	50.7686	96.4998	scour	344	5	single	very faint	na	na
278	1994	S	4	221	2048	50.7686	96.4998	LABA	187	1	single	faint	na	more diffuse to one side
279	1994	S	4	221	2050	50.7670	96.4980	scour	355	10	multiple	faint	na	na
280	1994	S	4	221	2052	50.7654	96.4965	scour	342	10	multiple	mod faint	na	na
281	1994	S	4	221	2053	50.7646	96.4956	scour	182	30	multiple	mod faint	na	na
282	1994	S	4	221	2056	50.7622	96.4930	LABA	359	12	single	faint	na	na
283	1994	S	4	221	2057	50.7614	96.4921	LABA	189	12	single	faint	na	na
284	1994	S	4	221	2057	50.7614	96.4921	LABA	182	12	single	faint	na	na
285	1994	S	4	221	2058	50.7606	96.4913	scour	198	15	multiple	faint	na	na
286	1994	S	4	221	2059	50.7597	96.4902	scour	188	20	multiple	faint	na	na
287	1994	S	4	221	2100	50.7586	96.4882	scour	197	30	multiple	mod faint	na	na
288	1994	S	4	221	2101	50.7581	96.4885	scour	195	20	multiple	very faint	na	na
289	1994	S	4	221	2106	50.7543	96.4846	scour	354	20	multiple	mod faint	na	na
290	1994	S	4	221	2106	50.7543	96.4846	LABA	199	15	single	mod faint	strong	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
291	1994	S	4	221	2108	50.7526	96.4830	scour	358	25	multiple	very faint	na	na
292	1994	S	4	221	2110	50.7510	96.4813	scour	354	20	multiple	faint	na	na
293	1994	S	4	221	2111	50.7502	96:4804	scour	221	15	single	very faint	na	na
294	1994	S	4	221	2112	50.7494	96.4796	scour	206	5	single	faint	na	na
295	1994	S	5	222	1454	50.8223	96.7519	scour	300	120	multiple	mod fresh	na	furrows
296	1994	S	5	222	1525	50.8430	96.7609	scour	256	10	single	na	na	poor record, 190-323 non-lin
297	1994	S	5	222	1603	50.8733	96.7376	scour	328	5	single	very faint	na	na
298	1994	S	5	222	1607	50.8764	96.7352	scour	310	5	single	very faint	na	na
299	1994	S	5	222	1608	50.8773	96.7343	scour	336	5	multiple	very faint	na	na
300	1994	S	5	222	1618	50.8852	96.7285	scour	331	20	multiple	mod fresh	na	na
301	1994	S	5	222	1622	50.8885	96.7259	scour	244	25	multiple	faint	na	na
302	1994	S	5	222	1623	50.8893	96.7253	scour	318	100	multiple	mod fresh	na	furrows
303	1994	S	5	222	1623	50.8893	96.7253	scour	318	100	multiple	mod fresh	na	furrows
304	1994	S	5	222	1625	50.8910	96.7241	scour	303	100	multiple	mod fresh	na	furrows
305	1994	S	5	222	1626	50.8917	96.7235	scour	318	100	multiple	mod fresh	na	na
306	1994	S	5	222	1627	50.8926	96.7228	scour	302	60	multiple	faint	na	furrows
307	1994	S	5	222	1629	50.8942	96.7216	LABA	329	15	single	fresh	strong	na
308	1994	S	5	222	1630	50.8949	96.7211	scour	306	10	na	very faint	na	na
309	1994	S	5	222	1630	50.8949	96.7211	scour	276	15	multiple	faint	na	na
310	1994	S	5	222	1633	50.8974	96.7193	LABA	307	8	single	mod fresh	na	only on 1 channel
311	1994	S	5	222	1634	50.8980	96.7187	scour	313	5	multiple	buried	na	na
312	1994	S	5	222	1636	50.8997	96.7173	scour	316	15	multiple	mod fresh	na	na
313	1994	S	5	222	1640	50.9029	96.7148	scour	292	55	multiple	mod fresh	na	na
314	1994	S	5	222	1645	50.9070	96.7117	scour	283	15	multiple	mod fresh	na	na
315	1994	S	5	222	1645	50.9070	96.7117	scour	276	30	multiple	mod buried	na	na
316	1994	S	5	222	1647	50.9086	96.7103	LABA	325	10	single	faint	na	na
317	1994	S	5	222	1654	50.9143	96.7060	scour	314	15	multiple	mod faint	na	sharp turn from 360-328
318	1994	S	5	222	1714	50.9304	96.6929	scour	183	15	multiple	mod buried	na	na
319	1994	S	5	222	1733	50.9460	96.6816	scour	337	150	multiple	mod fresh	na	na
320	1994	S	5	222	1744	50.9547	96.6750	scour	183	2	single	very faint	na	na
321	1994	S	5	222	1753	50.9619	96.6696	scour	192	100	multiple	mod fresh	na	buried furrows
322	1994	S	5	222	1754	50.9627	96.6690	scour	356	40	multiple	mod fresh	na	buried furrows
323	1994	S	5	222	1756	50.9643	96.6677	scour	181	40	multiple	buried	na	na
324	1994	S	5	222	1800	50.9675	96.6652	scour	212	8	single	na	na	na
325	1994	S	5	222	1804	50.9706	96.6625	scour	183	70	multiple	na	na	curving
326	1994	S	5	222	1807	50.9730	96.6605	scour	202	10	multiple	mod fresh	na	na
327	1994	S	5	222	1810	50.9755	96.6590	scour	180	15	multiple	mod fresh	na	na
328	1994	S	5	222	1812	50.9772	96.6577	scour	187	5	single	very faint	na	na
329	1994	S	5	222	1829	50.9908	96.6472	scour	193	40	multiple	mod faint	na	na
330	1994	S	5	222	1831	50.9920	96.6459	scour	357	120	multiple	mod faint	na	furrows
331	1994	S	5	222	1832	50.9932	96.6453	scour	180	10	multiple	faint	na	na
332	1994	S	5	222	1832	50.9932	96.6453	scour	262	100	multiple	very faint	na	na
333	1994	S	5	222	1832	50.9932	96.6453	LABA	193	10	single	fresh	na	na
334	1994	S	5	222	1834	50.9947	96.6440	scour	331	210	multiple	na	strong	furrows
335	1994	S	5	222	1835	50.9954	96.6434	scour	191	20	multiple	faint	na	na
336	1994	S	5	222	1835	50.9954	96.6434	scour	353	20	multiple	faint	na	na
337	1994	S	5	222	1837	50.9970	96.6421	scour	359	30	multiple	faint	na	na
338	1994	S	5	222	1840	50.9994	96.6403	LABA	330	25	single	na	strong	some relief
339	1994	S	5	222	1846	51.0042	96.6369	LABA	193	25	single	na	strong	na
340	1994	S	5	222	1902	51.0170	96.6269	LABA	200	25	single	buried	strong	na
341	1994	S	5	222	1907	51.0211	96.6239	scour	199	5	single	faint	na	na
342	1994	S	5	222	1907	51.0211	96.6239	scour	358	5	single	faint	na	na
343	1994	S	5	222	1908	51.0219	96.6232	scour	187	5	single	faint	na	na
344	1994	S	5	222	1911	51.0244	96.6213	scour	183	8	multiple	faint	na	na
345	1994	S	5	222	1912	51.0251	96.6207	scour	183	100	multiple	fresh	na	furrows
346	1994	S	5	222	1913	51.0259	96.6201	scour	292	35	multiple	buried	na	na
347	1994	S	5	222	1915	51.0276	96.6188	LABA	194	8	single	faint	na	na
348	1994	S	5	222	1917	51.0293	96.6176	scour	182	35	multiple	fresh	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
349	1994	S	5	222	1920	51.0317	96.6158	scour	183	250	multiple	fresh	na	some furrows
350	1994	S	5	222	1920	51.0317	96.6158	LABA	183	250	multiple	fresh	strong	na
351	1994	S	5	222	1958	51.0631	96.5914	LABA	188	15	single	buried	strong	na
352	1994	S	5	222	2010	51.0732	96.5837	scour	352	5	single	very faint	na	na
353	1994	S	5	222	2134	51.1430	96.5253	scour	202	40	multiple	very faint	na	na
354	1994	S	5	222	2140	51.1469	96.5185	LABA	203	15	single	very faint	moderate	na
355	1994	S	5	222	2140	51.1469	96.5185	scour	217	2	single	very faint	na	na
356	1994	S	5	222	2143	51.1489	96.5151	LABA	355	15	na	buried	moderate	na
357	1994	S	5	222	2144	51.1494	96.5141	LABA	343	7	na	buried	moderate	na
358	1994	S	6	223	1456	51.1653	96.4749	LABA	190	15	single	faint	moderate	na
359	1994	S	6	223	1605	51.1852	96.3746	scour	218	5	single	na	na	sandy, may not be a scour
360	1994	S	6	223	2147	51.4094	96.6332	LABA	350	10	single	mod fresh	na	na
361	1994	S	7	224	1532	51.6422	96.7561	scour	348	35	multiple	faint	na	na
362	1994	S	7	224	1532	51.6422	96.7561	scour	332	30	multiple	faint	na	na
363	1994	S	7	224	1544	51.6511	96.7550	scour	310	8	single	faint	na	na
364	1994	S	7	224	1618	51.6773	96.7527	scour	303	50	multiple	faint	na	non-linear
365	1994	S	7	224	1655	51.6888	96.7810	scour	349	50	multiple	faint	na	na
366	1994	S	7	224	1720	51.6925	96.8065	scour	311	5	single	faint	na	na
367	1994	S	7	224	1720	51.6925	96.8065	scour	328	5	single	faint	na	na
368	1994	S	7	224	1720	51.6925	96.8065	scour	196	5	single	faint	na	na
369	1994	S	7	224	1720	51.6925	96.8065	scour	346	5	single	faint	na	na
370	1994	S	7	224	1724	51.6937	96.8090	scour	354	5	multiple	fresh	na	na
371	1994	S	7	224	2049	51.8107	96.8612	scour	323	10	multiple	mod faint	na	na
372	1994	S	7	224	2049	51.8107	96.8612	scour	308	10	multiple	mod faint	na	na
373	1994	S	7	224	2102	51.8153	96.8789	scour	345	40	multiple	mod fresh	na	212-240
374	1994	N	8	227	1721	52.9271	97.7902	LABA	339	12	single	mod fresh	strong	na
375	1994	N	8	227	1822	52.8766	97.8305	scour	338	1	single	na	na	na
376	1994	N	8	227	1822	52.8766	97.8305	scour	182	1	multiple	na	na	na
377	1994	N	8	227	1822	52.8766	97.8305	scour	355	1	multiple	na	na	na
378	1994	N	8	227	1822	52.8766	97.8305	scour	298	1	single	na	na	na
379	1994	N	8	227	1822	52.8766	97.8305	scour	309	1	multiple	na	na	in Lake Agassiz sediments
380	1994	N	8	227	1829	52.8696	97.8366	scour	339	60	multiple	fresh	strong	na
381	1994	N	8	227	1836	52.8625	97.8428	LABA	339	10	single	mod fresh	strong	na
382	1994	N	8	227	1837	52.8615	97.8436	LABA	340	10	single	mod fresh	strong	na
383	1994	N	8	227	1841	52.8601	97.8502	LABA	325	5	single	na	strong	na
384	1994	N	8	227	1853	52.8584	97.8734	LABA	349	8	single	buried	na	na
385	1994	N	8	227	1858	52.8576	97.8831	scour	321	30	multiple	buried	na	na
386	1994	N	8	227	1905	52.8563	97.8967	scour	308	16	multiple	mod fresh	na	na
387	1994	N	8	227	1905	52.8563	97.8967	LABA	314	8	single	mod fresh	na	na
388	1994	N	8	227	1906	52.8561	97.8986	LABA	188	8	single	mod buried	na	na
389	1994	N	8	227	1913	52.8546	97.9125	scour	319	150	multiple	mod fresh	na	na
390	1994	N	8	227	1913	52.8546	97.9125	scour	344	10	multiple	mod fresh	na	na
391	1994	N	8	227	2109	52.8353	98.0640	LABA	356	15	single	mod fresh	moderate	only on left channel
392	1994	N	8	227	2110	52.8350	98.0653	LABA	358	10	single	mod faint	none	na
393	1994	N	8	227	2111	52.8348	98.0667	LABA	355	20	single	mod fresh	none	na
394	1994	N	8	227	2139	52.8483	98.0926	LABA	344	30	single	fresh	strong	na
395	1994	N	8	227	2314	52.9149	98.1741	scour	191	65	multiple	fresh	na	na
396	1994	N	8	227	2315	52.9157	98.1748	scour	187	60	multiple	buried	na	na
397	1994	N	8	227	2325	52.9229	98.1829	LABA	189	15	multiple	mod faint	weak	na
398	1994	N	8	227	2327	52.9244	98.1845	LABA	330	10	single	buried	na	na
399	1994	N	9	229	1149	53.6069	97.9657	scour	181	1	na	na	na	na
400	1994	N	9	229	1149	53.6069	97.9657	scour	347	5	single	na	na	in Lake Agassiz sediments
401	1994	N	9	229	1149	53.6069	97.9657	scour	334	1	na	na	na	na
402	1994	N	9	229	1149	53.6069	97.9657	scour	356	1	na	na	na	na
403	1994	N	9	229	1219	53.6064	98.0130	scour	191	10	single	very faint	na	na
404	1994	N	9	229	1219	53.6064	98.0130	scour	353	10	single	very faint	na	na
405	1994	N	9	229	1247	53.5913	98.0572	scour	357	30	multiple	very faint	na	na
406	1994	N	9	229	1253	53.5871	98.0667	scour	343	20	multiple	mod faint	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
407	1994	N	9	229	1309	53.5751	98.0920	LABA	341	2	single	buried	na	na
408	1994	N	9	229	1310	53.5744	98.0935	LABA	345	8	single	very buried	strong	na
409	1994	N	9	229	1323	53.5655	98:1141	scour	335	150	multiple	mod fresh	na	furrows
410	1994	N	9	229	1324	53.5646	98.1156	scour	338	25	multiple	mod faint	na	na
411	1994	N	9	229	1329	53.5612	98.1235	scour	181	15	multiple	buried	na	na
412	1994	N	9	229	1340	53.5534	98.1409	scour	330	100	multiple	mod fresh	na	furrows
413	1994	N	9	229	1350	53.5463	98.1567	LABA	326	20	single	mod fresh	strong	na
414	1994	N	9	229	1351	53.5456	98.1583	LABA	349	30	single	fresh	strong	na
415	1994	N	9	229	1355	53.5427	98.1646	scour	339	5	single	buried	na	na
416	1994	N	9	229	1406	53.5348	98.1819	scour	183	12	multiple	mod buried	na	na
417	1994	N	9	229	1413	53.5298	98.1930	scour	346	8	single	very faint	na	na
418	1994	N	9	229	1420	53.5249	98.2040	scour	338	40	multiple	very faint	na	na
419	1994	N	9	229	1438	53.5119	98.2325	scour	334	5	single	very faint	na	na
420	1994	N	9	229	1452	53.5020	98.2546	LABA	319	25	single	fresh	strong	na
421	1994	N	9	229	1453	53.5012	98.2561	scour	322	15	multiple	mod fresh	na	na
422	1994	N	9	229	1508	53.4907	98.2798	scour	334	5	single	buried	na	na
423	1994	N	9	229	1510	53.4892	98.2830	scour	313	60	multiple	buried	na	non-linear
424	1994	N	9	229	1528	53.4763	98.3114	LABA	335	25	single	buried	strong	na
425	1994	N	9	229	1536	53.4705	98.3240	LABA	313	8	single	fresh	moderate	furrows
426	1994	N	9	229	1545	53.4641	98.3382	LABA	314	10	single	mod fresh	strong	furrows
427	1994	N	9	229	1640	53.4244	98.4251	LABA	347	20	single	mod fresh	strong	na
428	1994	N	9	229	1642	53.4229	98.4282	scour	347	30	multiple	mod fresh	na	na
429	1994	N	9	229	1644	53.4212	98.4314	scour	337	20	multiple	mod fresh	na	na
430	1994	N	9	229	1649	53.4178	98.4393	LABA	340	20	single	fresh	strong	na
431	1994	N	9	229	1651	53.4165	98.4424	LABA	356	25	single	fresh	strong	na
432	1994	N	9	229	1653	53.4150	98.4456	LABA	301	15	single	fresh	strong	na
433	1994	N	9	229	1657	53.4121	98.4519	LABA	351	10	single	fresh	strong	na
434	1994	N	9	229	1707	53.4050	98.4677	scour	182	10	multiple	mod buried	na	na
435	1994	N	9	229	1713	53.4007	98.4772	scour	332	10	multiple	mod fresh	na	na
436	1994	N	9	229	1719	53.3963	98.4866	LABA	324	10	single	fresh	weak	na
437	1994	N	9	229	1722	53.3942	98.4914	scour	347	20	multiple	faint	na	na
438	1994	N	9	229	1728	53.3897	98.5008	scour	322	120	multiple	fresh	na	na
439	1994	N	9	229	1746	53.3768	98.5292	LABA	314	10	single	fresh	weak	na
440	1994	N	9	229	1750	53.3739	98.5356	scour	347	25	multiple	faint	na	na
441	1994	N	9	229	1751	53.3731	98.5371	scour	341	120	multiple	buried	na	na
442	1994	N	9	229	1753	53.3717	98.5403	scour	284	25	multiple	buried	na	na
443	1994	N	9	229	1756	53.3695	98.5450	LABA	328	25	single	fresh	weak	na
444	1994	N	9	229	1758	53.3680	98.5482	LABA	324	10	single	buried	moderate	na
445	1994	N	9	229	1758	53.3680	98.5482	LABA	200	10	single	fresh	moderate	na
446	1994	N	9	229	1800	53.3666	98.5513	scour	345	20	multiple	mod fresh	na	na
447	1994	N	9	229	1810	53.3594	98.5671	scour	341	5	single	buried	na	na
448	1994	N	9	229	1813	53.3573	98.5719	LABA	336	15	single	buried	moderate	na
449	1994	N	9	229	1814	53.3565	98.5735	scour	333	15	multiple	mod fresh	na	na
450	1994	N	9	229	1829	53.3456	98.5971	scour	185	15	multiple	mod fresh	na	na
451	1994	N	9	229	1829	53.3456	98.5971	scour	240	15	multiple	mod fresh	na	non-linear
452	1994	N	9	229	1830	53.3448	98.5987	scour	338	15	multiple	mod fresh	na	non-linear
453	1994	N	9	229	1831	53.3441	98.6003	scour	192	50	multiple	mod fresh	na	na
454	1994	N	9	229	1831	53.3441	98.6003	scour	337	20	multiple	mod fresh	na	na
455	1994	N	9	229	1832	53.3434	98.6019	scour	325	15	multiple	mod fresh	na	na
456	1994	N	9	229	1832	53.3434	98.6019	scour	279	50	multiple	mod fresh	na	na
457	1994	N	9	229	1832	53.3434	98.6019	scour	337	65	multiple	mod fresh	na	na
458	1994	N	9	229	1834	53.3419	98.6050	scour	351	15	multiple	mod fresh	na	na
459	1994	N	9	229	1838	53.3389	98.6113	scour	358	10	multiple	mod fresh	na	na
460	1994	N	9	229	1847	53.3324	98.6255	LABA	331	10	single	buried	strong	na
461	1994	N	9	229	1849	53.3309	98.6287	scour	335	10	multiple	mod fresh	na	na
462	1994	N	9	229	1851	53.3294	98.6319	scour	325	10	multiple	mod fresh	na	na
463	1994	N	9	229	1852	53.3287	98.6334	scour	334	10	multiple	buried	na	na
464	1994	N	9	229	1855	53.3265	98.6382	scour	292	8	multiple	mod fresh	na	non-linear, 210-270

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
465	1994	N	9	229	1856	53.3258	98.6396	LABA	181	15	single	buried	na	na
466	1994	N	9	229	1857	53.3250	98.6413	LABA	337	40	single	buried	strong	na
467	1994	N	9	229	1902	53.3214	98.6492	scour	345	15	multiple	buried	na	na
468	1994	N	9	229	1903	53.3207	98.6506	LABA	338	8	single	buried	na	na
469	1994	N	9	229	1907	53.3177	98.6571	scour	333	10	multiple	mod buried	na	na
470	1994	N	9	229	1909	53.3163	98.6603	LABA	355	5	single	buried	moderate	na
471	1994	N	9	229	1913	53.3134	98.6666	scour	324	35	multiple	mod buried	na	na
472	1994	N	9	229	1914	53.3127	98.6682	LABA	346	10	single	mod fresh	moderate	na
473	1994	N	9	229	1916	53.3112	98.6713	LABA	336	10	single	fresh	moderate	na
474	1994	N	9	229	1918	53.3098	98.6745	scour	320	15	multiple	buried	na	na
475	1994	N	9	229	1919	53.3091	98.6761	LABA	306	10	single	fresh	moderate	na
476	1994	N	9	229	1922	53.3069	98.6806	scour	320	10	multiple	buried	na	na
477	1994	N	9	229	1926	53.3039	98.6871	LABA	324	15	single	fresh	strong	na
478	1994	N	9	229	1934	53.2980	98.6997	scour	336	15	multiple	buried	na	na
479	1994	N	9	229	1939	53.2943	98.7076	scour	329	20	multiple	buried	na	na
480	1994	N	9	229	1940	53.2936	98.7092	scour	298	50	multiple	fresh	na	na
481	1994	N	9	229	1943	53.2914	98.7140	LABA	273	15	single	buried	strong	na
482	1994	N	9	229	1944	53.2907	98.7155	scour	333	10	multiple	mod fresh	na	na
483	1994	N	9	229	1946	53.2893	98.7187	LABA	318	15	single	fresh	moderate	na
484	1994	N	9	229	1947	53.2886	98.7203	scour	310	5	single	buried	na	na
485	1994	N	9	229	1947	53.2886	98.7203	LABA	356	17	single	fresh	moderate	na
486	1994	N	9	229	1948	53.2879	98.7218	scour	337	15	multiple	buried	na	na
487	1994	N	9	229	1951	53.2857	98.7266	LABA	335	10	single	mod fresh	moderate	na
488	1994	N	9	229	1952	53.2850	98.7282	scour	189	5	single	very buried	na	na
489	1994	N	9	229	2001	53.2787	98.7424	scour	335	15	multiple	buried	na	na
490	1994	N	9	229	2002	53.2782	98.7439	scour	300	5	single	buried	na	na
491	1994	N	9	229	2016	53.2679	98.7661	scour	277	10	multiple	mod buried	na	na
492	1994	N	9	229	2017	53.2672	98.7676	scour	183	10	multiple	mod fresh	na	na
493	1994	N	9	229	2018	53.2664	98.7692	LABA	275	20	single	fresh	strong	na
494	1994	N	9	229	2019	53.2656	98.7708	LABA	329	15	single	mod fresh	strong	na
495	1994	N	9	229	2019	53.2656	98.7708	LABA	334	15	single	mod fresh	strong	na
496	1994	N	9	229	2020	53.2649	98.7724	scour	286	50	multiple	mod buried	na	na
497	1994	N	9	229	2020	53.2649	98.7724	LABA	337	10	single	mod fresh	na	na
498	1994	N	9	229	2021	53.2642	98.7739	scour	325	50	multiple	mod buried	na	na
499	1994	N	9	229	2021	53.2642	98.7739	LABA	335	10	single	mod fresh	na	na
500	1994	N	9	229	2022	53.2635	98.7755	scour	335	30	multiple	buried	na	na
501	1994	N	9	229	2023	53.2627	98.7771	scour	330	10	multiple	buried	na	na
502	1994	N	9	229	2024	53.2620	98.7787	scour	329	10	multiple	mod buried	na	na
503	1994	N	9	229	2025	53.2613	98.7803	LABA	318	10	single	mod fresh	moderate	na
504	1994	N	9	229	2027	53.2598	98.7834	scour	186	5	single	very faint	na	na
505	1994	N	9	229	2028	53.2591	98.7850	LABA	342	10	single	mod fresh	moderate	na
506	1994	N	9	229	2028	53.2591	98.7850	scour	196	15	multiple	faint	na	na
507	1994	N	9	229	2028	53.2591	98.7850	scour	347	10	multiple	faint	na	na
508	1994	N	9	229	2029	53.2583	98.7866	scour	291	10	multiple	mod buried	na	na
509	1994	N	9	229	2029	53.2583	98.7866	scour	329	10	multiple	mod buried	na	na
510	1994	N	9	229	2030	53.2576	98.7882	LABA	217	15	single	faint	na	na
511	1994	N	9	229	2030	53.2576	98.7882	scour	348	18	multiple	mod fresh	na	na
512	1994	N	9	229	2033	53.2554	98.7929	scour	198	10	multiple	buried	na	na
513	1994	N	9	229	2034	53.2548	98.7945	LABA	198	10	single	mod buried	moderate	na
514	1994	N	9	229	2034	53.2548	98.7945	scour	318	10	multiple	buried	na	na
515	1994	N	9	229	2037	53.2525	98.7992	LABA	350	10	single	mod fresh	strong	na
516	1994	N	9	229	2038	53.2518	98.8008	LABA	353	13	single	mod fresh	strong	na
517	1994	N	9	229	2039	53.2510	98.8024	LABA	322	30	single	buried	strong	na
518	1994	N	9	229	2039	53.2510	98.8024	LABA	319	15	single	buried	strong	na
519	1994	N	9	229	2041	53.2495	98.8055	scour	334	60	multiple	buried	na	na
520	1994	N	9	229	2041	53.2495	98.8055	scour	189	50	multiple	mod fresh	na	na
521	1994	N	9	229	2044	53.2474	98.8103	LABA	327	20	single	buried	moderate	na
522	1994	N	9	229	2046	53.2459	98.8134	scour	302	5	single	mod buried	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
523	1994	N	9	229	2046	53.2459	98.8134	scour	192	20	multiple	mod buried	na	na
524	1994	N	9	229	2046	53.2459	98.8134	LABA	309	25	single	mod buried	strong	na
525	1994	N	9	229	2047	53.2452	98.8150	LABA	310	20	single	buried	strong	na
526	1994	N	9	229	2047	53.2452	98.8150	LABA	196	10	single	mod fresh	na	na
527	1994	N	9	229	2047	53.2452	98.8150	scour	344	30	multiple	mod fresh	na	na
528	1994	N	9	229	2050	53.2430	98.8197	LABA	215	10	single	very buried	moderate	na
529	1994	N	9	229	2053	53.2408	98.8245	LABA	182	20	single	buried	na	na
530	1994	N	9	229	2053	53.2408	98.8245	scour	215	20	multiple	mod fresh	na	na
531	1994	N	9	229	2054	53.2401	98.8260	LABA	319	8	single	buried	moderate	na
532	1994	N	9	229	2056	53.2386	98.8292	LABA	322	5	single	mod fresh	moderate	na
533	1994	N	9	229	2056	53.2386	98.8292	LABA	323	10	single	fresh	strong	na
534	1994	N	9	229	2057	53.2379	98.8308	LABA	320	12	single	na	na	na
535	1994	N	9	229	2057	53.2379	98.8308	LABA	322	10	multiple	mod fresh	moderate	na
536	1994	N	9	229	2057	53.2379	98.8308	LABA	325	15	single	buried	strong	na
537	1994	N	9	229	2058	53.2372	98.8324	LABA	319	15	single	buried	strong	na
538	1994	N	9	229	2058	53.2372	98.8324	LABA	328	15	single	buried	strong	na
539	1994	N	9	229	2103	53.2337	98.8402	LABA	201	15	single	mod fresh	moderate	na
540	1994	N	9	229	2104	53.2329	98.8418	LABA	196	25	single	mod buried	strong	na
541	1994	N	9	229	2107	53.2308	98.8466	LABA	205	30	single	fresh	strong	na
542	1994	N	9	229	2107	53.2308	98.8466	LABA	257	30	single	very buried	na	na
543	1994	N	9	229	2108	53.2301	98.8481	LABA	356	10	multiple	mod buried	strong	na
544	1994	N	9	229	2109	53.2294	98.8497	LABA	286	5	single	buried	moderate	na
545	1994	N	9	229	2109	53.2294	98.8497	LABA	310	10	single	mod fresh	strong	na
546	1994	N	9	229	2109	53.2294	98.8497	LABA	189	5	single	buried	moderate	na
547	1994	N	9	229	2110	53.2287	98.8513	LABA	318	20	single	fresh	strong	na
548	1994	N	9	229	2110	53.2287	98.8513	scour	354	15	multiple	faint	na	na
549	1994	N	9	229	2111	53.2280	98.8529	LABA	317	8	single	mod fresh	na	na
550	1994	N	9	229	2111	53.2280	98.8529	scour	312	10	multiple	buried	na	na
551	1994	N	9	229	2111	53.2280	98.8529	LABA	335	15	single	fresh	moderate	na
552	1994	N	9	229	2111	53.2280	98.8529	LABA	191	10	single	buried	na	na
553	1994	N	9	229	2111	53.2280	98.8529	LABA	224	20	single	fresh	na	turns then stops
554	1994	N	9	229	2113	53.2266	98.8560	scour	335	120	multiple	mod buried	na	na
555	1994	N	9	229	2114	53.2259	98.8576	LABA	300	10	single	buried	strong	na
556	1994	N	9	229	2115	53.2252	98.8592	LABA	301	10	single	buried	strong	na
557	1994	N	9	229	2115	53.2252	98.8592	LABA	310	7	single	mod fresh	strong	na
558	1994	N	9	229	2115	53.2252	98.8592	scour	336	15	multiple	buried	na	na
559	1994	N	9	229	2117	53.2237	98.8624	LABA	349	10	single	fresh	strong	na
560	1994	N	9	229	2118	53.2234	98.8639	LABA	271	8	single	buried	strong	na
561	1994	N	9	229	2122	53.2202	98.8702	LABA	355	8	single	fresh	moderate	na
562	1994	N	9	229	2122	53.2202	98.8702	LABA	185	2	single	mod buried	weak	na
563	1994	N	9	229	2123	53.2195	98.8718	LABA	355	20	single	fresh	strong	na
564	1994	N	9	229	2124	53.2192	98.8734	LABA	209	15	single	mod buried	na	na
565	1994	N	9	229	2125	53.2181	98.8750	LABA	274	35	multiple	fresh	strong	na
566	1994	N	9	229	2125	53.2181	98.8750	scour	181	15	multiple	buried	na	na
567	1994	N	9	229	2128	53.2160	98.8797	LABA	346	10	single	fresh	strong	na
568	1994	N	9	229	2130	53.2145	98.8829	LABA	278	30	multiple	mod fresh	strong	na
569	1994	N	9	229	2131	53.2138	98.8845	LABA	215	25	single	mod buried	strong	na
570	1994	N	9	229	2133	53.2124	98.8876	LABA	193	10	single	fresh	moderate	na
571	1994	N	9	229	2133	53.2124	98.8876	scour	280	5	single	buried	na	na
572	1994	N	9	229	2135	53.2110	98.8908	scour	300	5	single	buried	na	na
573	1994	N	9	229	2136	53.2103	98.8923	LABA	310	8	single	buried	moderate	na
574	1994	N	9	229	2141	53.2068	98.9002	LABA	198	5	single	mod fresh	na	na
575	1994	N	9	229	2141	53.2068	98.9002	scour	324	20	multiple	faint	na	na
576	1994	N	9	229	2141	53.2068	98.9002	scour	294	30	multiple	fresh	strong	proto-laba?
577	1994	N	9	220	2141	53.2068	98.9002	LABA	195	45	multiple	fresh	na	na
578	1994	N	9	229	2142	53.2061	98.9018	LABA	315	45	multiple	mod fresh	strong	na
579	1994	N	9	229	2143	53.2054	98.9034	LABA	310	5	single	mod buried	strong	na
580	1994	N	9	229	2144	53.2047	98.9050	LABA	340	8	multiple	mod buried	strong	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
581	1994	N	9	229	2144	53.2047	98.9050	LABA	338	15	multiple	mod buried	strong	na
582	1994	N	9	229	2145	53.2040	98.9066	LABA	339	40	multiple	mod fresh	moderate	na
583	1994	N	9	229	2145	53.2040	98:9066	LABA	201	8	single	very buried	na	na
584	1994	N	9	229	2146	53.2033	98.9081	LABA	335	10	single	mod fresh	moderate	na
585	1994	N	9	229	2147	53.2026	98.9097	LABA	317	8	multiple	buried	na	na
586	1994	N	9	229	2147	53.2026	98.9097	LABA	323	8	single	mod buried	strong	na
587	1994	N	9	229	2148	53.2019	98.9113	scour	198	15	multiple	faint	na	na
588	1994	N	9	229	2150	53.2004	98.9144	scour	329	15	multiple	buried	na	na
589	1994	N	9	229	2151	53.1998	98.9160	LABA	295	15	multiple	mod fresh	strong	na
590	1994	N	9	229	2151	53.1998	98.9160	LABA	350	10	single	buried	strong	na
591	1994	N	9	229	2152	53.1990	98.9176	scour	342	5	single	very buried	na	na
592	1994	N	9	229	2152	53.1990	98.9176	scour	335	5	single	very buried	na	na
593	1994	N	9	229	2152	53.1990	98.9176	LABA	316	10	single	na	strong	na
594	1994	N	9	229	2152	53.1990	98.9176	scour	292	5	single	very buried	na	na
595	1994	N	9	229	2152	53.1990	98.9176	LABA	213	10	single	mod fresh	strong	na
596	1994	N	9	229	2154	53.1976	98.9208	scour	207	40	multiple	buried	na	na
597	1994	N	9	229	2208	53.1878	98.9429	LABA	341	10	single	na	strong	na
598	1994	N	9	229	2211	53.1858	98.9476	LABA	310	30	multiple	buried	strong	na
599	1994	N	9	229	2220	53.1796	98.9618	scour	285	30	multiple	buried	na	na
600	1994	N	9	229	2224	53.1781	98.9681	LABA	334	30	single	mod buried	none	na
601	1994	N	9	229	2224	53.1781	98.9681	LABA	310	8	single	very buried	moderate	na
602	1994	N	9	229	2226	53.1768	98.9713	scour	300	20	multiple	mod fresh	na	non-linear, 302-193
603	1994	N	9	229	2234	53.1740	98.9839	scour	247	10	multiple	very buried	na	na
604	1994	N	9	229	2243	53.1777	98.9981	scour	240	5	single	buried	na	na
605	1994	N	9	229	2243	53.1777	98.9981	scour	235	10	multiple	buried	na	na
606	1994	N	9	229	2244	53.1781	98.9997	LABA	227	15	single	very buried	moderate	na
607	1994	N	9	229	2244	53.1781	98.9997	LABA	245	15	single	fresh	strong	na
608	1994	N	9	229	2246	53.1788	99.0029	LABA	239	10	single	mod fresh	strong	na
609	1994	N	9	229	2251	53.1806	99.0118	LABA	201	15	single	mod buried	strong	na
610	1994	N	9	229	2251	53.1806	99.0118	LABA	201	25	single	mod buried	strong	na
611	1994	N	9	229	2252	53.1810	99.0138	LABA	208	8	single	mod buried	strong	na
612	1994	N	9	229	2252	53.1810	99.0138	LABA	208	8	single	mod buried	strong	na
613	1994	N	9	229	2252	53.1810	99.0138	LABA	208	8	single	mod buried	strong	na
614	1994	N	9	229	2253	53.1814	99.0164	scour	191	25	multiple	buried	na	na
615	1994	N	9	229	2256	53.1824	99.0217	LABA	352	40	single	buried	strong	na
616	1994	N	9	229	2256	53.1824	99.0217	LABA	220	15	single	buried	strong	na
617	1994	N	9	229	2256	53.1824	99.0217	LABA	222	15	single	buried	strong	na
618	1994	N	9	229	2301	53.1843	99.0311	LABA	219	8	single	mod fresh	strong	na
619	1994	N	9	229	2302	53.1847	99.0331	scour	248	2	single	buried	na	na
620	1994	N	9	229	2302	53.1847	99.0331	scour	246	2	single	buried	na	na
621	1994	N	9	229	2303	53.1850	99.0350	LABA	234	30	single	mod fresh	strong	na
622	1994	N	9	229	2304	53.1854	99.0369	scour	233	2	single	buried	na	na
623	1994	N	9	229	2309	53.1871	99.0465	LABA	225	5	single	buried	strong	na
624	1994	N	9	229	2309	53.1871	99.0465	scour	324	15	multiple	faint	na	na
625	1994	N	9	229	2312	53.1883	99.0523	LABA	200	10	single	fresh	strong	na
626	1994	N	9	229	2312	53.1883	99.0523	LABA	203	30	single	mod fresh	none	end of laba
627	1994	N	9	229	2313	53.1886	99.0542	LABA	212	30	multiple	buried	strong	na
628	1994	N	9	229	2315	53.1894	99.0582	scour	197	60	multiple	mod fresh	na	na
629	1994	N	9	229	2316	53.1897	99.0602	scour	201	30	multiple	fresh	na	na
630	1994	N	9	229	2317	53.1901	99.0621	LABA	198	8	single	mod fresh	moderate	na
631	1994	N	9	229	2317	53.1901	99.0621	scour	197	35	multiple	mod fresh	na	na
632	1994	N	9	229	2318	53.1905	99.0640	LABA	229	2	single	buried	na	na
633	1994	N	9	229	2329	53.1945	99.0854	LABA	213	5	single	buried	strong	na
634	1994	N	9	229	2329	53.1945	99.0854	LABA	214	15	single	buried	strong	na
635	1994	N	9	229	2330	53.1949	99.0874	LABA	211	35	single	buried	strong	na
636	1994	N	10	230	1631	52.9724	98.2601	scour	210	8	single	fresh	na	na
637	1994	N	10	230	1651	52.9954	98.2683	scour	324	10	multiple	fresh	na	na
638	1994	N	10	230	1655	53.0002	98.2695	scour	326	20	multiple	faint	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
639	1994	N	10	230	1656	53.0014	98.2698	LABA	319	7	single	fresh	strong	na
640	1994	N	10	230	1656	53.0014	98.2698	LABA	306	8	single	fresh	strong	na
641	1994	N	10	230	1657	53.0026	98.2701	scour	327	10	multiple	fresh	na	na
642	1994	N	10	230	1659	53.0050	98.2707	LABA	304	15	single	fresh	strong	na
643	1994	N	10	230	1700	53.0062	98.2710	LABA	309	8	single	mod fresh	none	na
644	1994	N	10	230	1700	53.0062	98.2710	LABA	302	5	single	mod fresh	none	na
645	1994	N	10	230	1701	53.0074	98.2713	LABA	331	45	multiple	fresh	strong	na
646	1994	N	10	230	1702	53.0086	98.2716	scour	338	30	multiple	mod buried	na	na
647	1994	N	10	230	1703	53.0098	98.2718	scour	313	45	multiple	buried	na	na
648	1994	N	10	230	1704	53.0110	98.2721	LABA	309	45	multiple	fresh	strong	na
649	1994	N	10	230	1704	53.0110	98.2721	LABA	311	45	multiple	fresh	strong	na
650	1994	N	10	230	1735	53.0477	98.2812	scour	347	5	multiple	mod buried	na	na
651	1994	N	10	230	1736	53.0489	98.2815	scour	271	1	multiple	na	na	non-linear, 191-349
652	1994	N	10	230	1736	53.0489	98.2815	LABA	321	10	single	mod fresh	strong	na
653	1994	N	10	230	1737	53.0501	98.2818	LABA	288	20	single	buried	strong	na
654	1994	N	10	230	1737	53.0501	98.2818	LABA	288	30	single	buried	strong	na
655	1994	N	10	230	1737	53.0501	98.2818	LABA	288	10	single	buried	strong	na
656	1994	N	10	230	1745	53.0595	98.2840	scour	334	10	multiple	buried	na	na
657	1994	N	10	230	1757	53.0736	98.2875	LABA	335	10	single	very buried	na	na
658	1994	N	10	230	1817	53.0971	98.2932	LABA	230	20	single	fresh	strong	na
659	1994	N	10	230	1819	53.0995	98.2937	LABA	221	10	single	fresh	strong	na
660	1994	N	10	230	1820	53.1007	98.2940	LABA	223	10	single	fresh	strong	na
661	1994	N	10	230	1833	53.1160	98.2979	scour	319	2	single	very buried	na	na
662	1994	N	10	230	1850	53.1362	98.3028	scour	314	10	multiple	buried	na	na
663	1994	N	10	230	1854	53.1410	98.3040	scour	284	2	single	mod buried	na	na
664	1994	N	10	230	1904	53.1530	98.3069	scour	230	30	multiple	buried	na	na
665	1994	N	10	230	1906	53.1554	98.3075	scour	333	2	single	mod buried	na	na
666	1994	N	10	230	1940	53.1966	98.3176	LABA	308	10	single	fresh	strong	na
667	1994	N	10	230	1940	53.1966	98.3176	LABA	185	10	single	mod fresh	strong	na
668	1994	N	10	230	1953	53.2125	98.3215	scour	300	20	multiple	buried	na	na
669	1994	N	10	230	1955	53.2150	98.3221	scour	301	20	multiple	mod buried	na	na
670	1994	N	10	230	2003	53.2248	98.3246	scour	331	40	multiple	buried	na	na
671	1994	N	10	230	2017	53.2420	98.3287	LABA	341	10	single	mod fresh	moderate	na
672	1994	N	10	230	2033	53.2615	98.3335	LABA	298	5	single	mod fresh	moderate	na
673	1994	N	10	230	2052	53.2847	98.3393	LABA	183	15	single	buried	none	na
674	1994	N	10	230	2119	53.3173	98.3472	LABA	305	25	single	fresh	strong	na
675	1994	N	10	230	2156	53.3614	98.3581	scour	333	2	single	very buried	na	na
676	1994	N	10	230	2205	53.3722	98.3608	scour	329	30	multiple	mod fresh	na	end of scour
677	1994	N	10	230	2250	53.4254	98.3739	LABA	339	10	single	very buried	moderate	na
678	1994	S	11	231	1504	53.3089	98.7607	scour	324	5	single	very faint	na	na
679	1994	S	11	231	1505	53.3099	98.7603	scour	310	10	multiple	mod faint	na	na
680	1994	S	11	231	1505	53.3099	98.7603	scour	287	10	multiple	very faint	na	na
681	1994	S	11	231	1506	53.3111	98.7599	scour	343	5	single	mod faint	na	na
682	1994	S	11	231	1512	53.3180	98.7573	LABA	316	10	single	mod buried	moderate	na
683	1994	S	11	231	1513	53.3191	98.7568	LABA	311	10	single	mod fresh	strong	na
684	1994	S	11	231	1513	53.3191	98.7568	scour	325	12	multiple	mod fresh	na	na
685	1994	S	11	231	1514	53.3203	98.7564	scour	335	10	multiple	mod fresh	na	na
686	1994	S	11	231	1515	53.3215	98.7561	scour	323	10	multiple	mod fresh	na	na
687	1994	S	11	231	1516	53.3226	98.7556	scour	278	10	multiple	very faint	na	na
688	1994	S	11	231	1520	53.3272	98.7538	LABA	213	1	na	mod fresh	strong	non-linear, 360->213
689	1994	S	11	231	1522	53.3295	98.7530	LABA	266	1	single	buried	moderate	na
690	1994	S	11	231	1522	53.3295	98.7530	scour	320	15	multiple	mod faint	na	na
691	1994	S	11	231	1524	53.3318	98.7522	LABA	327	15	single	mod buried	strong	na
692	1994	S	11	231	1524	53.3318	98.7522	scour	296	30	multiple	buried	na	na
693	1994	S	11	231	1528	53.3363	98.7503	LABA	308	20	single	fresh	moderate	na
694	1994	S	11	231	1606	53.3799	98.7338	LABA	309	30	single	fresh	strong	na
695	1994	S	11	231	1610	53.3845	98.7320	scour	298	15	multiple	buried	na	na
696	1994	S	11	231	1625	53.4020	98.7254	LABA	306	10	single	na	none	stops and goes back out

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
697	1994	S	11	231	1626	53.4032	98.7250	LABA	308	1	multiple	na	none	terminates
698	1994	S	11	231	1627	53.4043	98.7245	LABA	307	1	single	fresh	strong	light bands, furrows
699	1994	S	11	231	1634	53.4124	98.7214	LABA	312	10	single	na	strong	furrows
700	1994	S	11	231	1650	53.4310	98.7143	scour	291	30	multiple	buried	na	na
701	1994	S	11	231	1703	53.4461	98.7086	LABA	320	10	single	fresh	strong	na
702	1994	S	11	231	1705	53.4484	98.7077	LABA	330	10	single	mod fresh	strong	na
703	1994	S	11	231	1738	53.4870	98.6930	LABA	315	10	single	na	strong	na
704	1994	S	11	231	1744	53.4941	98.6903	scour	310	10	multiple	buried	na	na
705	1994	S	11	231	1757	53.5094	98.6845	scour	295	150	multiple	fresh	na	large, with furrows and berms
706	1994	S	11	231	1757	53.5094	98.6845	scour	328	100	multiple	fresh	na	cross-cut by large feature
707	1994	S	11	231	1759	53.5117	98.6836	scour	334	15	multiple	fresh	na	na
708	1994	S	11	231	1800	53.5129	98.6832	scour	298	10	multiple	buried	na	na
709	1994	S	11	231	1804	53.5177	98.6813	LABA	325	100	multiple	fresh	strong	na
710	1994	S	11	231	1809	53.5236	98.6790	scour	356	10	multiple	mod buried	na	na
711	1994	S	11	231	1810	53.5248	98.6786	scour	307	60	multiple	mod buried	na	na
712	1994	S	11	231	1811	53.5260	98.6781	scour	309	40	multiple	mod fresh	na	laba turning into scour
713	1994	S	11	231	1811	53.5260	98.6781	LABA	308	15	single	fresh	strong	furrows
714	1994	S	11	231	1813	53.5284	98.6772	LABA	287	10	multiple	na	strong	furrows
715	1994	S	11	231	1814	53.5296	98.6768	scour	307	10	multiple	mod fresh	na	na
716	1994	S	11	231	1815	53.5308	98.6764	LABA	314	10	single	mod buried	none	na
717	1994	S	11	231	1818	53.5343	98.6750	LABA	310	30	single	fresh	strong	berms
718	1994	S	11	231	1823	53.5403	98.6727	scour	305	5	single	faint	na	na
719	1994	S	11	231	1832	53.5512	98.6685	scour	330	10	multiple	faint	na	na
720	1994	S	11	231	1842	53.5633	98.6639	scour	312	80	multiple	faint	na	furrows
721	1994	S	11	231	1843	53.5645	98.6635	LABA	324	30	single	fresh	strong	na
722	1994	S	11	231	1849	53.5717	98.6607	scour	312	60	multiple	faint	na	furrows
723	1994	S	11	231	1852	53.5753	98.6593	scour	318	100	multiple	fresh	na	furrows
724	1994	S	11	231	1904	53.5898	98.6537	scour	325	50	multiple	faint	na	furrows
725	1994	S	11	231	1906	53.5922	98.6530	LABA	320	30	single	fresh	strong	slight depression in lakefloor
726	1994	S	11	231	1917	53.6055	98.6479	scour	321	50	na	very faint	na	furrows
727	1994	S	11	231	1918	53.6067	98.6474	LABA	200	5	single	fresh	strong	na
728	1994	S	11	231	1924	53.6140	98.6446	scour	312	10	multiple	buried	na	na
729	1994	S	11	231	1928	53.6187	98.6427	LABA	289	10	single	fresh	strong	na
730	1994	S	11	231	1939	53.6321	98.6377	scour	309	100	multiple	fresh	na	furrows
731	1994	S	11	231	1940	53.6333	98.6371	scour	310	30	multiple	mod fresh	na	furrows
732	1994	S	11	231	1942	53.6355	98.6361	scour	302	50	multiple	mod fresh	na	furrows
733	1994	S	11	231	1942	53.6355	98.6361	LABA	300	1	single	fresh	strong	furrows
734	1994	S	11	231	1943	53.6368	98.6359	LABA	303	5	single	fresh	strong	furrows
735	1994	S	11	231	1944	53.6381	98.6358	scour	316	15	multiple	mod buried	na	na
736	1994	S	11	231	1946	53.6404	98.6345	LABA	308	8	single	na	strong	berms and furrows
737	1994	S	11	231	1946	53.6404	98.6345	LABA	308	8	single	na	strong	berms and furrows
738	1994	S	11	231	1947	53.6416	98.6341	LABA	308	8	single	na	strong	berms and furrows
739	1994	S	11	231	1947	53.6416	98.6341	LABA	308	8	single	na	strong	berms and furrows
740	1994	S	11	231	1948	53.6420	98.6339	LABA	308	8	single	na	strong	berms and furrows
741	1994	S	11	231	1948	53.6420	98.6339	LABA	308	8	single	na	strong	berms and furrows
742	1994	S	11	231	1949	53.6440	98.6331	LABA	306	8	single	na	strong	berms and furrows
743	1994	S	11	231	1949	53.6440	98.6331	LABA	308	8	single	na	strong	berms and furrows
744	1994	S	11	231	1949	53.6440	98.6331	LABA	306	10	single	na	strong	berms and furrows
745	1994	S	11	231	1950	53.6452	98.6327	LABA	306	20	single	na	strong	berms and furrows
746	1994	S	11	231	1951	53.6464	98.6322	LABA	306	20	single	na	strong	berms and furrows
747	1994	S	11	231	1952	53.6476	98.6316	LABA	306	30	single	na	strong	berms and furrows
748	1994	S	11	231	1952	53.6476	98.6316	LABA	306	30	single	na	strong	berms and furrows
749	1994	S	11	231	1953	53.6488	98.6311	LABA	306	15	single	na	strong	berms and furrows
750	1994	S	11	231	1953	53.6488	98.6311	LABA	306	30	single	na	strong	berms and furrows
751	1994	S	11	231	1954	53.6500	98.6307	LABA	308	10	single	fresh	strong	na
752	1994	S	11	231	1954	53.6500	98.6307	scour	308	10	multiple	mod buried	na	na
753	1994	S	11	231	1956	53.6525	98.6299	scour	309	10	multiple	mod buried	na	na
754	1994	S	11	231	1957	53.6537	98.6294	LABA	307	1	multiple	fresh	strong	berms and furrows

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
755	1994	S	11	231	2003	53.6937	98.6141	LABA	318	10	single	buried	strong	na
756	1994	S	11	231	2003	53.6937	98.6141	LABA	294	8	single	mod fresh	moderate	na
757	1994	S	11	231	2004	53.6621	98.6263	scour	296	2	single	very faint	na	na
758	1994	S	11	231	2004	53.6621	98.6263	scour	303	8	multiple	very faint	na	na
759	1994	S	11	231	2010	53.6694	98.6234	scour	332	2	single	very faint	na	na
760	1994	S	11	231	2016	53.6767	98.6206	scour	305	50	multiple	very faint	na	furrows
761	1994	S	11	231	2025	53.6876	98.6164	scour	250	30	multiple	mod fresh	na	na
762	1994	S	11	231	2026	53.6888	98.6159	scour	326	70	multiple	mod fresh	na	berms and furrows
763	1994	S	11	231	2031	53.6949	98.6136	scour	324	80	multiple	mod fresh	na	berms and furrows
764	1994	S	11	231	2034	53.6985	98.6122	scour	318	5	multiple	faint	na	na
765	1994	S	11	231	2034	53.6985	98.6122	scour	320	5	multiple	faint	na	na
766	1994	S	11	231	2050	53.7180	98.6047	scour	334	3	single	faint	na	na
767	1994	S	11	231	2053	53.7217	98.6034	scour	319	2	single	mod faint	na	na
768	1994	S	11	231	2058	53.7277	98.6011	scour	289	30	multiple	mod faint	na	na
769	1994	S	11	231	2101	53.7306	98.5999	scour	320	10	multiple	mod fresh	na	na
770	1996	S	12	222	1649	50.9101	96.7091	scour	226	1	na	na	na	na
771	1996	S	12	222	1649	50.9101	96.7091	scour	281	1	na	na	na	na
772	1996	S	12	222	1650	50.9110	96.7085	scour	195	1	na	na	na	na
773	1996	S	12	222	1650	50.9110	96.7085	scour	357	1	na	na	na	na
774	1996	S	12	222	1651	50.9120	96.7078	scour	221	1	na	na	na	na
775	1996	S	12	222	1651	50.9124	96.7075	scour	210	1	na	na	na	na
776	1996	S	12	222	1651	50.9120	96.7078	scour	208	1	na	na	na	na
777	1996	S	12	222	1652	50.9131	96.7069	LABA	233	3	single	faint	na	na
778	1996	S	12	222	1652	50.9128	96.7072	LABA	205	4	single	na	na	overprinted by oc
779	1996	S	12	222	1653	50.9133	96.7068	scour	207	1	na	na	na	na
780	1996	S	12	222	1654	50.9143	96.7060	scour	211	1	na	na	na	na
781	1996	S	12	222	1655	50.9152	96.7053	scour	274	1	na	na	na	na
782	1996	S	12	222	1657	50.9167	96.7042	scour	270	1	na	na	na	na
783	1996	S	12	222	1659	50.9188	96.7025	LABA	357	2	single	na	na	changes direction
784	1996	S	12	222	1700	50.9197	96.7019	scour	319	1	na	na	na	na
785	1996	S	12	222	1700	50.9197	96.7019	scour	288	1	na	na	na	na
786	1996	S	12	222	1701	50.9205	96.7012	LABA	273	2	single	na	na	linear
787	1996	S	12	222	1701	50.9205	96.7012	scour	318	1	na	na	na	na
788	1996	S	12	222	1701	50.9205	96.7012	LABA	318	2	single	na	na	linear
789	1996	S	12	222	1702	50.9207	96.7011	scour	294	1	na	na	na	na
790	1996	S	12	222	1702	50.9209	96.7009	scour	270	1	na	na	na	na
791	1996	S	12	222	1703	50.4472	96.8331	scour	319	1	na	na	na	na
792	1996	S	12	222	1703	50.4469	96.8336	scour	308	1	na	na	na	na
793	1996	S	12	222	1705	50.4482	96.8306	scour	305	1	na	na	na	na
794	1996	S	12	222	1706	50.4484	96.8302	LABA	356	4	single	faint	na	linear
795	1996	S	12	222	1706	50.4487	96.8294	scour	354	1	na	na	na	na
796	1996	S	12	222	1706	50.4487	96.8294	LABA	327	2	single	fresh	na	na
797	1996	S	12	222	1707	50.4489	96.8290	scour	322	1	na	na	na	na
798	1996	S	12	222	1709	50.4502	96.8266	scour	325	1	na	na	na	na
799	1996	S	12	222	1710	50.4509	96.8253	scour	194	1	na	na	na	na
800	1996	S	12	222	1711	50.4513	96.8242	scour	352	1	na	na	na	na
801	1996	S	12	222	1711	50.4514	96.8240	scour	343	1	na	na	na	na
802	1996	S	12	222	1711	50.4517	96.8234	scour	351	1	na	na	na	na
803	1996	S	12	222	1712	50.4523	96.8222	scour	347	1	na	na	na	na
804	1996	S	12	222	1713	50.4529	96.8210	scour	346	1	na	na	na	na
805	1996	S	12	222	1713	50.4525	96.8218	LABA	342	2	single	mod fresh	na	na
806	1996	S	12	222	1714	50.4532	96.8204	scour	353	1	na	na	na	na
807	1996	S	12	222	1714	50.4531	96.8206	scour	347	1	na	na	na	na
808	1996	S	12	222	1714	50.4532	96.8204	LABA	340	2	single	mod fresh	na	na
809	1996	S	12	222	1714	50.4535	96.8198	scour	343	1	na	na	na	na
810	1996	S	12	222	1715	50.4536	96.8193	scour	351	1	na	na	na	na
811	1996	S	12	222	1719	50.4560	96.8143	scour	328	1	na	na	na	na
812	1996	S	12	222	1719	50.4560	96.8143	scour	348	1	na	na	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
813	1996	S	12	222	1720	50.4567	96.8131	scour	185	1	na	na	na	na
814	1996	S	12	222	1721	50.4572	96.8119	LABA	185	3	single	mod fresh	na	na
815	1996	S	12	222	1722	50.4581	96.8101	scour	347	1	na	na	na	na
816	1996	S	12	222	1722	50.4577	96.8109	scour	356	1	na	na	na	na
817	1996	S	12	222	1723	50.4584	96.8095	LABA	181	6	single	mod fresh	na	na
818	1996	S	12	222	1723	50.4587	96.8089	scour	182	1	na	na	na	na
819	1996	S	12	222	1724	50.4590	96.8083	scour	359	1	na	na	na	na
820	1996	S	12	222	1725	50.4596	96.8071	scour	325	1	na	na	na	na
821	1996	S	12	222	1728	50.4612	96.8037	scour	195	1	na	na	na	na
822	1996	S	12	222	1728	50.4612	96.8037	scour	336	1	na	na	na	na
823	1996	S	12	222	1729	50.4618	96.8023	scour	187	1	na	na	na	na
824	1996	S	12	222	1729	50.4618	96.8025	scour	339	1	na	na	na	na
825	1996	S	12	222	1730	50.4624	96.8011	scour	352	1	na	na	na	na
826	1996	S	12	222	1733	50.4642	96.7975	scour	195	1	na	na	na	na
827	1996	S	12	222	1733	50.4642	96.7975	LABA	333	6	single	faint	na	na
828	1996	S	12	222	1735	50.4654	96.7950	LABA	282	3	single	na	na	kinked
829	1996	S	12	222	1735	50.4654	96.7950	scour	346	1	na	na	na	na
830	1996	S	12	222	1736	50.4662	96.7934	scour	344	1	na	na	na	na
831	1996	S	12	222	1737	50.4669	96.7919	scour	354	1	na	na	na	na
832	1996	S	12	222	1737	50.4666	96.7925	scour	185	1	na	na	na	na
833	1996	S	12	222	1738	50.4674	96.7909	LABA	338	5	single	faint	na	na
834	1996	S	12	222	1738	50.4675	96.7907	LABA	331	7	single	faint	na	na
835	1996	S	12	222	1739	50.4678	96.7900	scour	183	1	na	na	na	na
836	1996	S	12	222	1739	50.4678	96.7900	scour	281	1	na	na	na	na
837	1996	S	12	222	1739	50.4681	96.7894	scour	340	1	na	na	na	na
838	1996	S	12	222	1739	50.4681	96.7894	scour	357	1	na	na	na	na
839	1996	S	12	222	1740	50.4687	96.7882	scour	181	1	na	na	na	na
840	1996	S	12	222	1740	50.4684	96.7888	scour	286	1	na	na	na	na
841	1996	S	12	222	1741	50.4693	96.7869	LABA	340	1	single	mod faint	na	na
842	1996	S	12	222	1741	50.4690	96.7875	LABA	342	3	single	mod fresh	na	na
843	1996	S	12	222	1741	50.4690	96.7875	scour	345	1	na	na	na	na
844	1996	S	12	222	1742	50.4699	96.7857	scour	357	1	na	na	na	na
845	1996	S	12	222	1742	50.4696	96.7863	scour	352	1	na	na	na	na
846	1996	S	12	222	1742	50.4696	96.7863	scour	321	1	na	na	na	na
847	1996	S	12	222	1743	50.4704	96.7844	scour	351	1	na	na	na	na
848	1996	S	12	222	1743	50.4704	96.7844	scour	335	1	na	na	na	na
849	1996	S	12	222	1744	50.4711	96.7832	scour	346	1	na	na	na	na
850	1996	S	12	222	1745	50.4717	96.7820	LABA	338	3	single	mod faint	na	na
851	1996	S	12	222	1745	50.4717	96.7820	LABA	351	1	single	mod faint	na	na
852	1996	S	12	222	1746	50.4720	96.7814	scour	344	1	na	na	na	na
853	1996	S	12	222	1847	50.5143	96.6935	scour	339	1	na	na	na	na
854	1996	S	12	222	1847	50.5146	96.6927	scour	354	1	na	na	na	na
855	1996	S	12	222	1847	50.5146	96.6927	LABA	340	3	single	faint	na	na
856	1996	S	12	222	1847	50.5143	96.6935	scour	356	1	na	na	na	na
857	1996	S	12	222	1848	50.5150	96.6919	LABA	329	5	single	mod faint	na	na
858	1996	S	12	222	1848	50.5150	96.6919	scour	304	1	na	na	na	na
859	1996	S	12	222	1849	50.5158	96.6903	LABA	346	8	single	faint	na	na
860	1996	S	12	222	1850	50.5166	96.6887	scour	343	1	na	na	na	na
861	1996	S	12	222	1850	50.5170	96.6878	LABA	332	17	single	mod faint	na	na
862	1996	S	12	222	1851	50.5174	96.6870	scour	357	1	na	na	na	na
863	1996	S	12	222	1851	50.5177	96.6862	LABA	344	2	single	na	na	curved
864	1996	S	12	222	1852	50.5181	96.6854	scour	336	1	na	na	na	na
865	1996	S	12	222	1853	50.5189	96.6838	scour	349	1	na	na	na	na
866	1996	S	12	222	1854	50.5201	96.6814	LABA	311	1	single	na	na	linear
867	1996	S	12	222	1854	50.5197	96.6822	scour	334	1	na	na	na	na
868	1996	S	12	222	1856	50.5212	96.6790	scour	349	1	na	na	na	na
869	1996	S	12	222	1857	50.5224	96.6765	scour	351	1	na	na	na	na
870	1996	S	12	222	1858	50.5232	96.6749	LABA	318	1	single	faint	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
871	1996	S	12	222	1900	50.5248	96.6717	LABA	185	2	single	faint	na	na
872	1996	S	12	222	1900	50.5244	96.6725	LABA	347	1	single	faint	na	na
873	1996	S	12	222	1900	50.5248	96.6717	LABA	344	3	single	faint	na	na
874	1996	S	12	222	1901	50.5252	96.6709	scour	333	1	na	na	na	na
875	1996	S	12	222	1903	50.5268	96.6675	scour	333	1	na	na	na	na
876	1996	S	12	222	1906	50.5270	96.6669	scour	304	1	na	na	na	na
877	1996	S	12	222	1907	50.5270	96.6668	scour	247	1	na	na	na	na
878	1996	S	12	222	1907	50.5270	96.6668	scour	256	1	na	na	na	na
879	1996	S	12	222	1907	50.5270	96.6668	scour	248	1	na	na	na	na
880	1996	S	12	222	1923	51.0342	96.6137	LABA	355	5	single	mod fresh	na	na
881	1996	S	12	222	1923	51.0346	96.6134	LABA	193	2	single	mod faint	na	na
882	1996	S	12	222	1924	51.0350	96.6131	LABA	350	6	single	mod faint	na	na
883	1996	S	12	222	1925	51.0362	96.6121	scour	347	1	na	na	na	na
884	1996	S	12	222	1926	51.0367	96.6118	scour	187	1	na	na	na	na
885	1996	S	12	222	1926	51.0371	96.6115	scour	338	1	na	na	na	na
886	1996	S	12	222	1928	51.0383	96.6106	LABA	209	2	single	mod faint	na	na
887	1996	S	12	222	1928	51.0387	96.6103	scour	189	1	na	na	na	na
888	1996	S	12	222	1929	51.0391	96.6099	scour	215	1	na	na	na	na
889	1996	S	12	222	1929	51.0391	96.6099	scour	210	1	na	na	na	na
890	1996	S	12	222	1929	51.0391	96.6099	scour	336	1	na	na	na	na
891	1996	S	12	222	1930	51.0399	96.6093	scour	196	1	na	na	na	na
892	1996	S	14	226	1600	50.9355	96.8464	LABA	183	17	multiple	faint	na	na
893	1996	S	14	226	1603	50.9354	96.8428	scour	196	2	na	na	na	na
894	1996	S	14	226	1607	50.9354	96.8367	scour	353	2	na	na	na	na
895	1996	S	14	226	1614	50.9355	96.8257	scour	357	23	na	na	na	na
896	1996	S	14	226	1620	50.9354	96.8163	scour	191	13	na	na	na	na
897	1996	S	14	226	1621	50.9354	96.8147	scour	197	21	na	na	na	na
898	1996	S	14	226	1622	50.9354	96.8131	scour	262	17	na	na	na	na
899	1996	S	14	226	1623	50.9354	96.8115	scour	326	2	na	na	na	na
900	1996	S	14	226	1623	50.9354	96.8106	scour	187	3	na	na	na	na
901	1996	S	14	226	1623	50.9354	96.8115	scour	198	12	na	na	na	na
902	1996	S	14	226	1626	50.9354	96.8065	scour	357	23	na	na	na	na
903	1996	S	14	226	1626	50.9354	96.8065	LABA	292	5	single	mod faint	na	na
904	1996	S	14	226	1627	50.9355	96.8048	scour	186	14	na	na	na	na
905	1996	S	14	226	1627	50.9355	96.8048	scour	341	2	na	na	na	na
906	1996	S	14	226	1628	50.9353	96.8033	scour	352	2	na	na	na	na
907	1996	S	14	226	1629	50.9354	96.8017	LABA	357	4	single	mod faint	na	na
908	1996	S	14	226	1634	50.9354	96.7931	scour	355	10	na	na	na	na
909	1996	S	14	226	1635	50.9354	96.7923	scour	357	21	na	na	na	na
910	1996	S	14	226	1635	50.9354	96.7915	scour	353	11	na	na	na	na
911	1996	S	14	226	1636	50.9354	96.7899	scour	340	3	na	na	na	na
912	1996	S	14	226	1636	50.9354	96.7907	scour	358	7	na	na	na	na
913	1996	S	14	226	1638	50.9354	96.7867	scour	187	13	na	na	na	na
914	1996	S	14	226	1639	50.9354	96.7862	LABA	358	2	single	mod faint	na	na
915	1996	S	14	226	1639	50.9354	96.7859	scour	189	20	na	na	na	na
916	1996	S	14	226	1640	50.9355	96.7836	scour	357	7	na	na	na	na
917	1996	S	14	226	1640	50.9355	96.7843	scour	195	16	na	na	na	na
918	1996	S	14	226	1641	50.9355	96.7828	scour	317	4	na	na	na	na
919	1996	S	14	226	1641	50.9354	96.7820	scour	337	1	na	na	na	na
920	1996	S	14	226	1641	50.9354	96.7820	scour	335	2	na	na	na	na
921	1996	S	14	226	1643	50.9355	96.7788	LABA	337	3	single	na	na	na
922	1996	S	14	226	1645	50.9354	96.7765	scour	351	17	na	na	na	na
923	1996	S	14	226	1646	50.9353	96.7749	scour	338	4	na	na	na	na
924	1996	S	14	226	1647	50.9354	96.7726	scour	272	1	na	na	na	na
925	1996	S	14	226	1647	50.9354	96.7734	scour	340	3	na	na	na	na
926	1996	S	14	226	1647	50.9354	96.7726	scour	185	1	na	na	na	na
927	1996	S	14	226	1648	50.9354	96.7718	LABA	180	5	single	mod fresh	na	na
928	1996	S	14	226	1648	50.9354	96.7718	scour	219	1	na	na	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
929	1996	S	14	226	1654	50.9354	96.7623	scour	280	1	na	na	na	na
930	1996	S	14	226	1654	50.9354	96.7623	scour	344	30	na	na	na	na
931	1996	S	14	226	1700	50.9354	96.7530	scour	357	20	na	na	na	na
932	1996	S	14	226	1702	50.9355	96.7499	scour	180	10	na	na	na	na
933	1996	S	14	226	1703	50.9354	96.7484	LABA	182	4	single	mod fresh	na	na
934	1996	S	14	226	1706	50.9353	96.7436	LABA	202	2	single	mod fresh	na	na
935	1996	S	14	226	1710	50.9354	96.7373	LABA	202	3	single	mod fresh	na	na
936	1996	S	14	226	1713	50.9355	96.7326	scour	348	30	na	na	na	na
937	1996	S	14	226	1714	50.9352	96.7311	scour	207	2	na	na	na	na
938	1996	S	14	226	1718	50.9355	96.7242	scour	356	5	na	na	na	na
939	1996	S	14	226	1719	50.9354	96.7235	scour	356	4	na	na	na	na
940	1996	S	14	226	1722	50.9355	96.7189	LABA	350	4	single	na	na	curved
941	1996	S	14	226	1723	50.9352	96.7174	scour	343	1	na	na	na	na
942	1996	S	14	226	1724	50.9354	96.7151	scour	187	1	na	na	na	na
943	1996	S	14	226	1725	50.9355	96.7144	scour	193	2	na	na	na	na
944	1996	S	14	226	1726	50.9357	96.7128	scour	201	8	na	na	na	na
945	1996	S	14	226	1755	50.9355	96.6679	scour	189	2	na	na	na	na
946	1996	S	14	226	1812	50.9353	96.6424	scour	353	80	na	na	na	na
947	1996	S	14	226	1840	50.9355	96.5995	scour	352	64	na	na	na	na
948	1996	S	14	226	1914	50.9354	96.5426	scour	340	2	na	na	na	na
949	1996	S	14	226	1916	50.9355	96.5393	scour	184	5	na	na	na	na
950	1996	S	14	226	1916	50.9355	96.5401	scour	185	2	na	na	na	na
951	1996	S	14	226	1917	50.9354	96.5376	scour	197	1	na	na	na	na
952	1996	S	14	226	1925	50.9354	96.5248	scour	194	1	na	na	na	na
953	1996	S	14	226	1931	50.9353	96.5146	scour	359	1	na	na	na	na
954	1996	S	14	226	1941	50.9353	96.4967	scour	185	2	na	na	na	na
955	1996	S	14	226	1945	50.9352	96.4908	scour	328	1	na	na	na	na
956	1996	N	16	228	1533	51.8816	96.9471	scour	194	1	na	na	na	na
957	1996	N	16	228	1533	51.8816	96.9471	scour	344	1	na	na	na	na
958	1996	N	16	228	1533	51.8816	96.9471	scour	221	1	na	na	na	na
959	1996	N	16	228	1606	51.9167	96.9720	scour	213	3	na	na	na	na
960	1996	N	16	228	1607	51.9178	96.9728	scour	346	1	na	na	na	na
961	1996	N	16	228	1616	51.9266	96.9791	LABA	233	3	single	faint	na	na
962	1996	N	16	228	1631	51.9425	96.9905	scour	302	4	na	na	na	na
963	1996	N	16	228	1639	51.9509	96.9965	scour	348	1	na	na	na	na
964	1996	N	16	228	1700	51.9728	97.0121	scour	346	16	na	na	na	na
965	1996	N	16	228	1713	51.9863	97.0218	LABA	324	2	single	faint	na	na
966	1996	N	16	228	1714	51.9874	97.0225	scour	191	3	na	na	na	na
967	1996	N	16	228	1715	51.9884	97.0232	scour	346	3	na	na	na	na
968	1996	N	16	228	1742	52.0162	97.0431	scour	195	1	na	na	na	na
969	1996	N	16	228	1827	52.0649	97.0779	scour	308	1	na	na	na	na
970	1996	N	16	228	1835	52.0730	97.0837	LABA	328	2	single	faint	na	na
971	1996	N	16	228	1901	52.1012	97.1039	scour	320	1	na	na	na	na
972	1996	N	16	228	1902	52.1029	97.1051	scour	291	2	na	na	na	na
973	1996	N	16	228	1918	52.1196	97.1171	scour	353	1	na	na	na	na
974	1996	N	16	228	1925	52.1273	97.1226	scour	209	1	na	na	na	na
975	1996	N	16	228	1927	52.1294	97.1242	scour	195	1	na	na	na	na
976	1996	N	16	228	1938	52.1416	97.1329	scour	347	4	na	na	na	na
977	1996	N	16	228	2002	52.1687	97.1523	scour	358	1	na	na	na	na
978	1996	N	16	228	2002	52.1682	97.1519	scour	187	1	na	na	na	na
979	1996	N	16	228	2002	52.1682	97.1519	scour	348	1	na	na	na	na
980	1996	N	16	228	2007	52.1737	97.1559	scour	347	2	na	na	na	na
981	1996	N	16	228	2007	52.1737	97.1559	LABA	322	2	single	mod fresh	na	na
982	1996	N	16	228	2019	52.1871	97.1655	scour	355	5	na	na	na	na
983	1996	N	16	228	2020	52.1882	97.1663	scour	347	1	na	na	na	na
984	1996	N	16	228	2033	52.2027	97.1768	scour	323	1	na	na	na	na
985	1996	N	16	228	2035	52.2050	97.1783	scour	325	1	na	na	na	na
986	1996	N	16	228	2046	52.2171	97.1872	scour	322	1	na	na	na	na

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987	1996	N	16	228	2102	52.2347	97.1997	scour	348	11	na	na	na	na
988	1996	N	16	228	2105	52.2380	97.2020	scour	193	1	na	na	na	na
989	1996	N	16	228	2106	52.2391	97.2028	scour	350	15	na	na	na	na
990	1996	N	16	228	2106	52.2391	97.2028	scour	313	1	na	na	na	na
991	1996	N	16	228	2110	52.2435	97.2060	scour	348	1	na	na	na	na
992	1996	N	16	228	2137	52.2742	97.2071	LABA	325	2	single	faint	na	na
993	1996	N	16	228	2146	52.2847	97.2009	scour	335	7	na	na	na	na
994	1996	N	16	228	2147	52.2852	97.2003	scour	344	3	na	na	na	na
995	1996	N	16	228	2147	52.2852	97.2003	scour	182	10	na	na	na	na
996	1996	N	18	233	1421	52.7829	97.6204	LABA	301	2	single	na	na	na
997	1996	N	18	233	1422	52.7814	97.6205	LABA	295	3	single	na	na	na
998	1996	N	18	233	1423	52.7809	97.6206	LABA	227	4	single	na	na	na
999	1996	N	18	233	1425	52.7788	97.6207	scour	228	1	multiple	na	na	na
1000	1996	N	18	233	1425	52.7788	97.6207	scour	334	8	multiple	na	na	na
1001	1996	N	18	233	1429	52.7748	97.6210	scour	336	6	multiple	na	na	terminates
1002	1996	N	18	233	1429	52.7748	97.6210	scour	322	7	multiple	na	na	na
1003	1996	N	18	233	1435	52.7684	97.6216	LABA	312	2	single	na	na	na
1004	1996	N	18	233	1441	52.7630	97.6220	scour	312	7	multiple	na	na	na
1005	1996	N	18	233	1446	52.7575	97.6224	scour	303	8	multiple	na	na	na
1006	1996	N	18	233	1447	52.7570	97.6225	scour	307	8	multiple	na	na	na
1007	1996	N	18	233	1450	52.7540	97.6227	scour	327	15	multiple	na	na	na
1008	1996	N	18	233	1451	52.7531	97.6228	scour	305	3	multiple	na	na	na
1009	1996	N	18	233	1452	52.7521	97.6229	scour	331	10	multiple	na	na	na
1010	1996	N	18	233	1504	52.7399	97.6239	LABA	292	1	single	na	na	na
1011	1996	N	18	233	1507	52.7374	97.6240	LABA	325	3	single	na	na	na
1012	1996	N	18	233	1510	52.7340	97.6244	LABA	316	2	single	na	na	na
1013	1996	N	18	233	1514	52.7301	97.6246	LABA	284	2	single	na	na	na
1014	1996	N	18	233	1515	52.7291	97.6247	scour	290	5	multiple	na	na	na
1015	1996	N	18	233	1518	52.7267	97.6249	scour	355	2	multiple	na	na	na
1016	1996	N	18	233	1521	52.7237	97.6252	scour	349	5	multiple	na	na	na
1017	1996	N	18	233	1521	52.7237	97.6252	LABA	264	6	single	na	na	terminates
1018	1996	N	18	233	1558	52.6879	97.6224	scour	326	2	multiple	na	na	curved
1019	1996	N	18	233	1603	52.6831	97.6211	scour	325	26	multiple	na	na	na
1020	1996	N	18	233	1609	52.6773	97.6198	scour	208	10	multiple	na	na	na
1021	1996	N	18	233	1615	52.6717	97.6183	LABA	302	2	single	na	na	na
1022	1996	N	18	233	1616	52.6707	97.6181	scour	321	26	multiple	na	na	na
1023	1996	N	18	233	1620	52.6669	97.6171	scour	322	5	multiple	na	na	na
1024	1996	N	18	233	1622	52.6650	97.6166	scour	323	10	multiple	na	na	na
1025	1996	N	18	233	1626	52.6612	97.6157	scour	312	13	multiple	na	na	na
1026	1996	N	18	233	1628	52.6592	97.6152	scour	306	4	multiple	na	na	na
1027	1996	N	18	233	1632	52.6554	97.6143	scour	323	4	multiple	na	na	na
1028	1996	N	18	233	1633	52.6544	97.6140	scour	298	14	multiple	na	na	na
1029	1996	N	18	233	1634	52.6530	97.6136	scour	321	9	multiple	na	na	na
1030	1996	N	18	233	1634	52.6530	97.6136	scour	305	9	multiple	na	na	na
1031	1996	N	18	233	1635	52.6525	97.6135	scour	338	10	multiple	na	na	na
1032	1996	N	18	233	1635	52.6525	97.6135	scour	324	13	multiple	na	na	na
1033	1996	N	18	233	1638	52.6497	97.6128	scour	327	8	multiple	faint	na	na
1034	1996	N	18	233	1638	52.6492	97.6127	scour	236	7	multiple	na	na	na
1035	1996	N	18	233	1640	52.6478	97.6123	scour	335	20	multiple	na	na	na
1036	1996	N	18	233	1640	52.6478	97.6123	scour	236	10	multiple	na	na	na
1037	1996	N	18	233	1643	52.6449	97.6116	scour	187	21	multiple	na	na	na
1038	1996	N	18	233	1644	52.6440	97.6114	scour	315	17	multiple	na	na	na
1039	1996	N	18	233	1646	52.6421	97.6109	scour	316	11	multiple	na	na	na
1040	1996	N	18	233	1646	52.6421	97.6109	scour	320	17	multiple	na	na	na
1041	1996	N	18	233	1648	52.6402	97.6104	scour	330	12	multiple	na	na	na
1042	1996	N	18	233	1649	52.6393	97.6102	LABA	300	1	single	na	na	na
1043	1996	N	18	233	1650	52.6384	97.6099	scour	333	11	multiple	na	na	na
1044	1996	N	18	233	1705	52.6240	97.6064	LABA	308	2	single	na	na	na

	Year	Basin	Line	Day	Time	Lat	Long	Type	Orient	Width	Keel	Strength	Reflector	Comment
1045	1996	N	18	233	1705	52.6244	97.6065	LABA	204	4	single	na	na	na
1046	1996	N	18	233	1738	52.5928	97.5986	scour	314	12	multiple	na	na	na
1047	1996	N	18	233	1739	52.5918	97.5983	LABA	285	12	single	na	na	na
1048	1996	N	18	233	1800	52.5694	97.5927	scour	321	1	multiple	na	na	na
1049	1996	N	18	233	1811	52.5580	97.5899	scour	319	4	multiple	na	na	na
1050	1996	N	18	233	1822	52.5472	97.5872	scour	205	1	single	faint	na	na
1051	1996	N	18	233	1825	52.5441	97.5864	scour	315	1	multiple	na	na	na
1052	1996	N	18	233	1828	52.5405	97.5855	LABA	297	7	multiple	na	na	na
1053	1996	N	18	233	1842	52.5264	97.5820	LABA	299	2	single	na	na	na
1054	1996	N	18	233	1842	52.5269	97.5821	LABA	299	2	single	na	na	na
1055	1996	N	18	233	1857	52.5117	97.5783	LABA	238	1	single	na	na	na
1056	1996	N	18	233	1911	52.4970	97.5746	scour	319	1	multiple	na	na	na
1057	1996	N	18	233	1913	52.4955	97.5742	scour	210	12	multiple	faint	na	na
1058	1996	N	18	233	1915	52.4934	97.5737	scour	333	1	multiple	na	na	na
1059	1996	N	18	233	1916	52.4924	97.5734	LABA	286	2	single	na	na	na
1060	1996	N	18	233	1918	52.4904	97.5730	scour	332	9	multiple	faint	na	na
1061	1996	N	19	234	1310	52.8878	97.7623	scour	315	3	single	faint	na	in Lake Agassiz sediments
1062	1996	N	19	234	1311	52.8891	97.7631	scour	317	3	single	faint	na	na
1063	1996	N	19	234	1314	52.8912	97.7646	scour	319	3	single	faint	na	in Lake Agassiz sediments
1064	1996	N	19	234	1318	52.8945	97.7672	scour	314	9	multiple	faint	na	in Lake Agassiz sediments
1065	1996	N	19	234	1319	52.8955	97.7678	scour	342	10	multiple	faint	na	in Lake Agassiz sediments
1066	1996	N	19	234	1320	52.8968	97.7687	scour	299	3	multiple	faint	na	in Lake Agassiz sediments
1067	1996	N	19	234	1320	52.8964	97.7684	scour	310	2	single	faint	na	in Lake Agassiz sediments
1068	1996	N	19	234	1320	52.8968	97.7687	scour	301	11	multiple	faint	na	in Lake Agassiz sediments
1069	1996	N	19	234	1325	52.9010	97.7717	scour	180	22	multiple	faint	na	in Lake Agassiz sediments
1070	1996	N	19	234	1354	52.9259	97.7897	LABA	341	2	single	na	na	na
1071	1996	N	19	234	1508	52.9932	97.8393	LABA	329	2	single	na	na	na
1072	1996	N	19	234	1512	52.9970	97.8423	LABA	322	3	single	na	na	na
1073	1996	N	19	234	1516	53.0011	97.8452	scour	315	15	multiple	faint	na	in Lake Agassiz sediments
1074	1996	N	19	234	1518	53.0037	97.8471	scour	314	1	single	faint	na	na
1075	1996	N	19	234	1528	53.0134	97.8543	scour	321	3	multiple	faint	na	na
1076	1996	N	19	234	1638	53.0613	97.9372	LABA	181	3	single	na	na	na
1077	1996	N	19	234	1638	53.0611	97.9363	LABA	189	2	single	na	na	na
1078	1996	N	19	234	1640	53.0615	97.9397	LABA	355	3	multiple	na	na	na
1079	1996	N	19	234	1642	53.0620	97.9432	LABA	188	1	single	na	na	na
1080	1996	N	19	234	1643	53.0622	97.9449	scour	189	2	multiple	na	na	na
1081	1996	N	19	234	1643	53.0623	97.9458	LABA	197	7	single	na	na	na
1082	1996	N	19	234	1644	53.0624	97.9467	scour	202	1	single	na	na	na
1083	1996	N	19	234	1648	53.0632	97.9537	LABA	242	1	single	na	na	na
1084	1996	N	19	234	1648	53.0632	97.9537	scour	281	4	multiple	faint	na	na
1085	1996	N	19	234	1649	53.0634	97.9555	LABA	241	3	single	na	na	na
1086	1996	N	19	234	1653	53.0642	97.9624	LABA	348	4	single	na	na	na
1087	1996	N	19	234	1659	53.0654	97.9723	scour	357	1	single	na	na	na
1088	1996	N	19	234	1702	53.0660	97.9773	LABA	196	4	single	na	na	na
1089	1996	N	19	234	1703	53.0662	97.9789	LABA	359	2	single	na	na	na
1090	1996	N	19	234	1705	53.0666	97.9821	LABA	180	1	single	na	na	na
1091	1996	N	19	234	1714	53.0682	97.9965	LABA	335	1	single	na	na	na
1092	1996	N	19	234	1722	53.0700	98.0106	LABA	351	1	single	na	na	na
1093	1996	N	19	234	1726	53.0708	98.0169	LABA	182	1	multiple	na	na	na
1094	1996	N	19	234	1733	53.0720	98.0273	LABA	358	2	single	na	na	na
1095	1996	N	19	234	1733	53.0721	98.0281	LABA	348	2	single	na	na	na
1096	1996	N	19	234	1750	53.0753	98.0556	LABA	350	1	single	na	na	na
1097	1996	N	19	234	1751	53.0757	98.0582	LABA	342	3	single	na	na	na